

NASA Contractor Report 158998

NASA-CR-158998

1979 0012872

SUMMARY REPORT

Evaluation of Laminar Flow Control System Concepts for Subsonic Commercial Transport Aircraft

BCAC Preliminary Design Department

BOEING COMMERCIAL AIRPLANE COMPANY
Seattle, Washington 98124

CONTRACT NAS1-14630
January 1979



National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665



NF01319

PREFACE

This document constitutes the summary report covering engineering development and evaluation of laminar flow control system concepts under Contract NAS1-14630. This effort is titled: "Evaluation of Laminar Flow Control System Concepts for Subsonic Commercial Transport Aircraft." Work was conducted in three major tasks: 1) Mission Definition and Baseline Configuration Development, 2) Concepts Evaluation, and 3) Configuration Selection and Design. The report covers the work conducted from September 1976 through September 1978. The NASA technical monitor for the entire period of the contract was Mr. J. W. Cheely of the Laminar Flow Control Project Office at Langley Research Center.

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1.0 SUMMARY

This report presents the results of a 2-year study carried out under NASA Contract NAS1-14630 in Phase I to extend the development of laminar flow control (LFC) technology and evaluate LFC systems concepts. The overall objective of the LFC program is to provide a sound basis for industry decisions on the application of LFC to future commercial transports. The study was organized into major tasks to support the stated objectives through application of LFC systems concepts to a baseline LFC transport initially generated for the study. Based on competitive evaluation of these concepts, a final selection was made for incorporation into the final design of an LFC transport which also included other advanced technology elements appropriate to the 1990 time period. In support of this activity, Boeing has expended company resources in basic LFC design studies and development of test facilities, including an LFC wing panel wind tunnel model to carry out wind tunnel tests at near full-scale Reynolds numbers.

Phase I of the LFC program has produced substantial accomplishments which will serve as a base for further progress. These can be summarized as follows:

1. A feasible structural concept has been defined which shows promise of evolving into a practical design that can be built and operated for reasonable costs. The fiberglass cover approach makes this concept adaptable to most structural arrangements including those using graphite/epoxy composites. However, extensive design development is still required to reduce weight and cost and to resolve operational and manufacturing concerns. Validation of the concept by analysis and testing is an essential step in advancing the design to a state of readiness for production.
2. The aerodynamic design of the LFC wing has been developed to the point where it could serve as a basis for further refinement in the wind tunnel. This development has been supported by wind tunnel tests on a representative LFC wing panel to provide design guidelines and evaluation of the effects of disturbances and off-design conditions. Advanced high-speed airfoils have been shown analytically to be compatible with LFC requirements and to provide a reasonable envelope to incorporate LFC systems and ducting. Although basic laminar boundary layer stability methods are becoming established, validation and streamlining of these methods for design purposes is necessary. The current aerodynamic design appears viable, but further refinement is necessary to minimize drag and reduce internal flow losses. Other objectives should include reducing sensitivity to off-design operation and various disturbances, minimizing the number of slots and reducing the criticality of the leading edge. Ultimately, inflight validation of the aerodynamic design is required throughout the operating envelope.
3. The additional systems required to implement application of LFC to a transport design have been identified. They are (1) the suction unit and associated ducting, (2) a device to protect the leading edge from insect accretion, and (3) subsystems to control suction distribution and monitor LFC performance. Design options in the first category have been evaluated, and a selection has been made for incorporation in a final airplane configuration.

Several promising approaches have been identified for the leading edge protection system, but further innovation and development are needed to arrive at a practical solution. The identification of control and monitoring systems is incomplete as might be expected for the current stage of LFC development.

4. Key operational problems have been identified and explored. The most important are: (1) wing leading edge damage, (2) insect contamination, (3) operational reliability, particularly in the presence of ice clouds, and (4) added maintenance costs and more difficult repair requirements. Solutions to these problems must be developed and validated either in the laboratory or in flight before serious consideration of LFC application to a production airplane can proceed.
5. An LFC transport configuration has been generated. It incorporates the most promising structural arrangement and systems concepts developed during this study. Combining other elements of advanced technology with LFC provides attractive fuel utilization benefits (70% improvement relative to the 747 airplane), which will have a very favorable impact on airplane economics. The effect of LFC alone, for a cycled design of the type presented here, is estimated to improve fuel economy by nearly 45% relative to an advanced turbulent design. Nevertheless, further trade studies are needed to define the combination of features that will lead to a design most competitive with a turbulent airplane. In particular, more work is necessary to establish better design criteria and operational requirements (e.g., turbulent climb capability and optimum cruise altitude). Such factors have been shown to have a substantial influence on airplane performance and economics.

2.0 INTRODUCTION

The implementation of new initiatives by NASA to develop laminar flow control (LFC) technology is due largely to the urgency of the energy problem and the realization that successful application to long-range transport aircraft can produce substantial improvement in fuel economy and airline economics.

The USAF-Northrop X-21A airplane program in the early 1960's (Ref. 1) was a major effort to demonstrate the feasibility of LFC on large subsonic aircraft. While substantial success in maintaining laminar flow was achieved, significant design compromises and the lack of overall reliability in a variety of flight conditions left many technical and operational questions unresolved and raised serious concern about the eventual adaptability of LFC to practical operation. In this light, the need for further research and development became obvious and provided the justification for the NASA laminar flow control program which has been planned in three phases to culminate in the design, development and flight testing of a demonstrator aircraft. The demonstrator will be flown under representative conditions to establish the economic and operational feasibility of this type of aircraft in airline service.

The subject of this report is the work accomplished by Boeing during Phase I of the LFC program under contract to NASA. The study was directed toward the further development of LFC technology and finding solutions to critical problems which must be solved before practical application of LFC can be successful. The overall objective of the LFC program is to provide a sound basis for industry decisions on the application of LFC to future commercial transports.

The study was organized into a series of major tasks and subtasks to develop and evaluate the most promising LFC concepts applicable to commercial air transports. The study approach is illustrated in Figure 2.0-1 which shows the major elements involved, their sequencing and the interaction between the activities. The result of the first task was the definition of a baseline aircraft to serve as the basis for LFC systems concepts evaluation and trade studies. Concurrent with the development and evaluation of candidate concepts, a series of parametric studies established tradeoff relationships between airplane geometry and design requirements. This interactive effort led to a selection of system concepts for incorporation in the final LFC airplane configuration. The final configuration design was accomplished in the last step which included the calculation of the airplane performance and comparison of its fuel efficiency with that of a representative turbulent transport aircraft.

Many of the technical problems associated with an LFC airplane are considered routine engineering developments similar to those expected in any new aircraft of more conventional design. Therefore, the tasks were limited to address problems uniquely related to LFC systems. This has resulted in the selection of concepts and systems for incorporation into a final LFC airplane design judged to have the highest probability of success consistent with safety and airline operational suitability. It has also yielded a strong technical and design base for the further development and testing in later phases of the program.

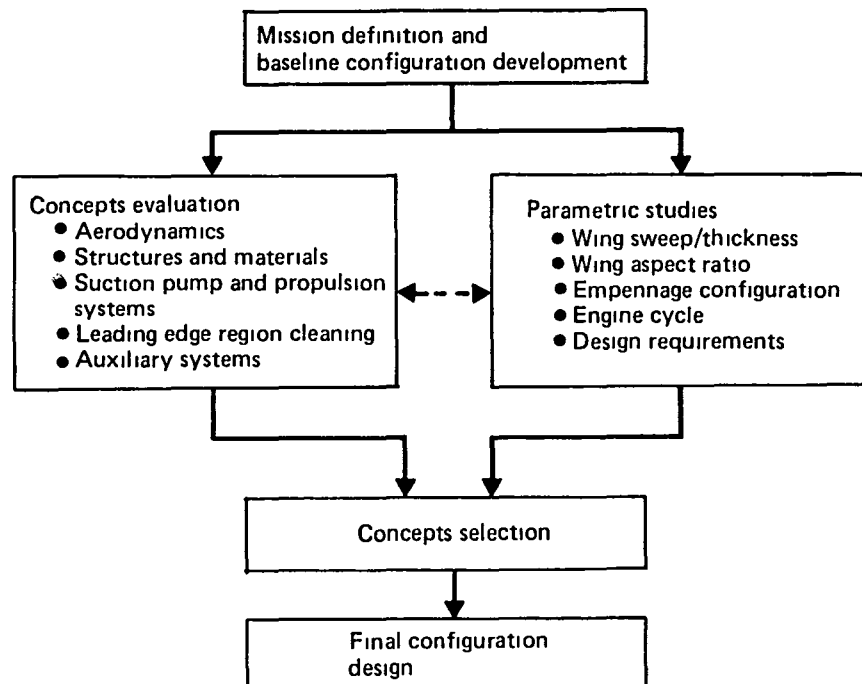


Figure 2.0-1. Study Approach

In support of the study, Boeing devoted company resources to initiating and expanding certain study elements and to providing improved test facilities. Toward this end, the Boeing Low-Speed Research Wind Tunnel was modified to provide valid laminar flow data at high Reynolds numbers. In addition, the design and construction of a large swept wing LFC model was accomplished. This combination was used successfully to carry out selected investigations under a variety of conditions representing critical flight situations. Major objectives included: (1) verification of airfoil leading edge design, (2) validation of suction flow requirements at high Reynolds numbers, (3) definition of allowable disturbances, including noise and (4) exploration of sensitivity to off-design conditions.

Major emphasis was also placed on the development of structural concepts for LFC wings. The definition of attractive design options and the generation of sufficient data to permit credible evaluation of these options based on structural integrity and manufacturing producibility was a primary goal of these studies. This activity, which led to a structural concept selection, was supported by limited hardware and environmental tests as appropriate to this stage of the development process. Sample hardware to indicate manufacturing feasibility is also provided to support the conclusions of the studies.

The technical team assigned to the program has continued to draw on government and industry experience with LFC. Consulting agreements with United Airlines and the Northrop Corporation were arranged to support the contract work during the entire period. Working agreements with Pratt & Whitney Aircraft and AiResearch Manufacturing Company provided for exchange of data on a mutual interest basis.

The following sections of this document provide a detailed reporting of the technical activity according to the major tasks defined in the original work statement of the contract, NAS1-14630, as modified by supplemental agreement (Amendment/Modification No. 6) dated October 1, 1977. The reporting also reflects changes effected through rescheduling via the C-63 forms during the contract period. The report is organized into chapters which, starting with Chapter 4.0 and continuing through Chapter 6.0, have titles corresponding to the major study tasks. These are: 4.0--Mission Definition and Baseline Configuration Development, 5.0--Concepts Evaluation and 6.0--Configuration Selection and Design. The sections in Chapter 5.0 are also titled to correspond with the subtasks which are included in the concepts evaluation task.

3.0 SYMBOLS AND ABBREVIATIONS

A	disturbance amplitude
AR	aspect ratio
b	wing span
BPR	bypass ratio
c	airfoil chord length
C_D	drag coefficient
c_d	local section drag coefficient
c_{d_w}	local wake drag coefficient
c_{d_s}	local equivalent suction drag coefficient
C_L	lift coefficient
C_p	pressure coefficient
C_Q	integrated suction flow coefficient
C_q	local suction flow coefficient
d	diameter of disk-type surface protuberances
DOC	direct operating cost
EPNL	effective perceived noise level
EPNdB	effective perceived noise decibel (unit of EPNL)
f	frequency
FAR	Federal Aviation Regulations
h	altitude
KEAS	equivalent airspeed in knots
k	height of surface protuberance or wave amplitude
L/D	lift to drag ratio

M	Mach number
MAC	Mean aerodynamic chord
OEW	operating empty weight
P	pressure
P&WA	Pratt & Whitney Aircraft
Q	suction flow rate
q	dynamic pressure
Re	Reynolds number
Re _l	unit Reynolds number
Re _s	slot Reynolds number
Re _{$\theta_{a.l.}$}	momentum thickness Reynolds number at the leading edge attachment line
S	wing area
s	distance along airfoil surface measured from leading edge
Δs	slot spacing
SFC	specific fuel consumption
SPF/DB	super plastic formed/diffusion bonded
SLST	sea level static thrust
t	wing thickness
TOGW	takeoff gross weight
u _h	velocity fluctuation derived from hot-wire measurement
u _m	velocity fluctuation derived from microphone data
V _{∞}	freestream velocity
V _A	approach speed
V _s	slot inflow velocity

v_w	distributed suction inflow velocity
W	weight
w	crossflow velocity component within the boundary layer
w_s	slot width
x	distance from leading edge measured along airfoil chord
y	distance from longitudinal axis measured along the span
z	distance from wing surface; also, airfoil ordinate perpendicular to the chord

Greek Symbols

α	angle of attack
η	spanwise position on wing in fraction of semi-span
H	wing twist angle
θ	boundary layer momentum thickness
λ	wing taper ratio; also, wave length
Λ	wing sweep angle, refers to 1/4 chord line unless otherwise noted
ρ	air density

Subscripts

a.l.	airflow attachment line on wing leading edge
max	maximum value
n	value based on normal chord
o	reference or initial condition; also, pertinent to leading edge
s	slot or suction
∞	freestream condition
w	wake or wall condition

4.0 MISSION DEFINITION AND BASELINE CONFIGURATION DEVELOPMENT

The initial task, titled Mission Definition and Baseline Configuration, was directed toward the selection of mission requirements representative of an LFC transport application projected for the 1990 time period and the generation of such a design suitable for tradeoff analyses in the subsequent concept evaluation tasks.

The baseline airplane design requirements are shown in Table 4.0-1, including factors that define the design mission for the airplane. The latter were defined on the basis of preliminary marketing and economic sensitivity studies. The corresponding operating envelope is given in Figure 4.0-1. Only the principal LFC operating envelope and the design point were used as a basis for evaluation studies. Initially, they were treated as design objectives subject to later validation rather than firm operational requirements.

The advanced technology base used for the baseline airplane was selected to be appropriate for an LFC airplane entry into service in the 1990 time period. In addition to the LFC itself, the use of advanced high-speed airfoils constitutes the principal aerodynamic advance. In the structural category, the use of improved aluminum alloys and the application of bonded construction to the fuselage and empennage is contemplated. An advanced technology turbofan similar to that identified in the EEE program studies (e.g., $\Delta SFC = -14\%$ and $\Delta \text{weight} = -13\%$) has been shown to be appropriate for an LFC transport.

No consideration was initially given to such items as laminarized empennage, composite structures, and wing load alleviation. Advancement in the technology base corresponding to these items was reserved for definition during the final LFC airplane design process.

Table 4.0-1. Baseline Airplane Design Requirements

Item	Value
Design range	10 190 km(5500 nmi)
Payload	201 passengers
Cruise mach number	0.8
Cruise altitude	12 800m (initial) (42 000 ft)
Turbulent climb capability	1.52 m/s at 10 670m (300 ft/min at 35 000 ft)
Takeoff field length	3566m (11 700 ft), or less
Approach speed	250 km/h (135 kn)
Fuel reserves	1967 ATA international rules (turbulent flow)

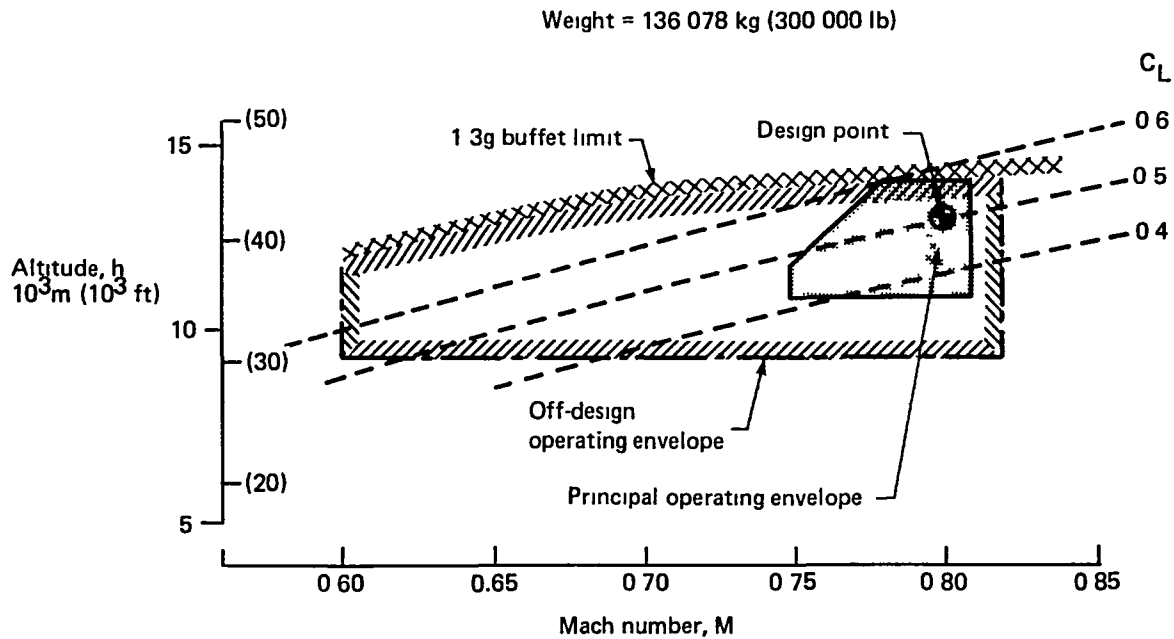


Figure 4.0-1. LFC Baseline Airplane Operating Envelope

The final version of the baseline airplane is a long-range, wide-body trijet designated Model 767-807. A three-view drawing of this configuration is presented in Figure 4.0- 2 and details of the airplane characteristics are presented in Table 4.0-2. The wing is laminarized to 70% chord on both the upper and lower surfaces. This permits the use of an outboard aileron for low-speed operation only, with the remainder of the span occupied by single-slotted Fowler flaps and 10% chord spoilers to provide high-speed lateral control and the normal speed brake functions. The two LFC suction units are located at the planform break, with suction airflow converging at this point from both wing root and wing tip. The engines are located on the aft body to provide a clean wing and minimize the influence of noise on the stability of the laminar boundary layer. The T-tail empennage is selected to be compatible with the aft-engine location and to provide greater potential trim drag reduction. Other characteristics of the airplane are quite representative of those found on a conventional turbulent long-range transport.

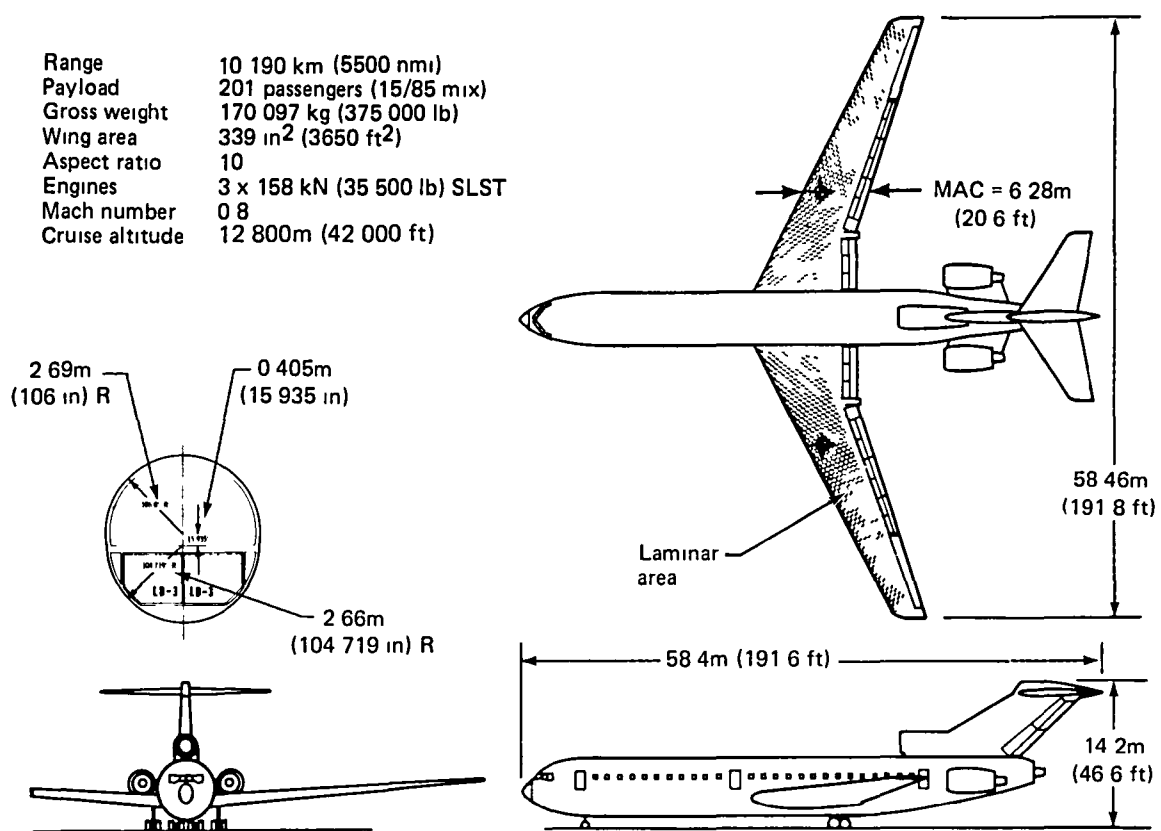


Figure 4.0-2. LFC Baseline Airplane—Model 767-807

Table 4.0-2. Baseline Airplane Characteristics—Model 767-807

Item	Value
Gross weight	170 097 kg (375 000 lb)
OEW	97 849 kg (215 720 lb)
Block fuel	46 103 kg (101 640 lb)
Reserves	7 040 kg (15 520 lb)
Landing weight	124 216 kg (273 850 lb)
Wing area	339 m ² (3650 ft ²)
Aspect ratio	10
Thickness ratio	0.14/0.11
Sweep	25 deg
Horizontal tail area	61.2 m ² (659 ft ²)
Vertical tail area	64.4 m ² (693 ft ²)
Body length/diameter	50.29m/5.38m (165 ft/212 in)
Engines (3-STF482)	158 kN (35 500 lb, SLST)
OEW/TOGW	0.576
Payload/TOGW	0.114
T/W	0.284
W/S	502 kg/m ² (103 lb/ft ²)
TOFL at SL, 29°C (84°F)	2.347m (7700 ft)
V _A	250 km/h (135 kn)

5.0 CONCEPTS EVALUATION

The objectives of this task were to evaluate the options available for aerodynamic design, structural concepts, and subsystems selection for a feasible LFC commercial transport. The evaluation included an assessment of the benefits versus complexity and cost for development, production and operation. This task was the predominant effort in the program. It was divided into the following five subtasks: (1) Aerodynamics, (2) Structures and Materials, (3) Suction Pump and Propulsion System, (4) Leading Edge Region Cleaning and (5) Auxiliary Systems.

5.1 AERODYNAMICS

The purpose of the task reported in this section was to develop solutions to the basic problems of LFC wing design and the aerodynamic systems required to assure reliable operation of the LFC airplane throughout the flight envelope and in a realistic operating environment. Thus, major attention was given to the determination of the appropriate parameters for an LFC wing consistent with advanced high-speed airfoil concepts and the airplane design requirements and objectives. Also, a major effort to obtain critical data in the wind tunnel to support successful wing design was carried on during the contract.

5.1.1 DESIGN REQUIREMENTS AND OBJECTIVES

In describing the aerodynamic design of the present LFC study airplane, it is appropriate to review first the major operational requirements that must be considered. These can be classified into four basic groups: (1) environmental considerations, (2) manufacturing tolerances, (3) maintenance requirements and (4) LFC systems requirements.

5.1.1.1 Environmental Considerations

Four major environmental considerations that impact the aerodynamic design are:

- a. Ice crystals (cruise altitude)
- b. Noise (engine placement)
- c. Insect contamination (wing leading edge design)
- d. Erosion (suction surface design)

The presence of ice crystals is widespread throughout the upper atmosphere and can substantially influence the choice of cruise altitude even on a daily basis. Based on data measured over Kwajalein atoll throughout the late summer months (Ref. 2), it is apparent that, near the equator, the ice particle distribution is such that some loss of LFC could be expected a substantial fraction of time. At higher latitudes, available evidence indicates that the critical particle distributions occur at lower altitudes and tend to diminish rapidly above the tropopause. Thus, an LFC airplane capable of cruise above 12 190m (40 000 ft) could operate reliably over most of the major airline routes. However, long-range routes involving penetration

of the lower latitudes would apparently need additional aids such as weather monitoring, and particle sensors, to permit economic operation. Additional data are needed to provide a clear understanding of the operational requirements associated with ice clouds and the design requirements for cruise altitude capability.

It is well known that noise emanating from the propulsion or suction engines could upset the proper functioning of LFC and lead to early transition of the laminar boundary layer to turbulent conditions. This, of course, must be considered in the aerodynamic design regarding engine placement. Previous studies, (Refs. 1, and 3) have established criteria for allowable noise disturbance levels and they served as guidelines for the present work.

Insect contamination or, more precisely, its prevention must be considered in the aerodynamic design at least to the extent that the airfoil section and the leading edge region of the wing must be suitable to accommodate some type of an insect deposit prevention device.

Erosion due to rain (or snow, hail, sand, etc.) also has an impact on the aerodynamic design of the leading edge. This is reflected in restrictions on location of the first slot and the selection of wing sweep. Also, the definition of leading edge material is an important consideration in minimizing the impact of erosion on airplane operations.


5.1.1.2 Manufacturing Tolerances

The sensitivity of laminar flow to surface irregularities, especially at high Reynolds numbers, is well known. Hence, the establishment of appropriate manufacturing tolerances for an LFC airplane is of critical importance. This problem has been studied in the past and some guidelines have been established, but the understanding is not yet complete and more work needs to be done. The main types of surface irregularities to be considered are: (1) waviness, (2) surface discontinuities such as steps, gaps, grooves, etc., (3) isolated protuberances such as rivets, fasteners, etc., (4) surface roughness such as graininess and scratches, and (5) slot discrepancies such as burrs, mismatches, and width inconsistencies.

It must be kept in mind, however, that most existing criteria were derived from experiments at low Mach numbers. Surface waves induce local pressure peaks that are amplified at higher Mach numbers. These waviness-induced pressure peaks tend to cause either a change in slot inflow or the occurrence of shock waves both of which can reduce the reliability and effectiveness of LFC. Nevertheless, for the current studies, tolerance criteria for discontinuities, protuberances and surface waviness have been based on References 4, 5 and 6. Based on preliminary estimates, significant Mach number effects are not anticipated within these tolerance limits.

5.1.1.3 Maintenance Requirements

The aerodynamic design must also consider certain requirements related to maintenance. One of these is the need to provide access holes into the wing so that structure can be inspected from inside. But laminarization of the access hole



cover plates appears to be quite difficult; thus, a portion of the wing area on the lower surface may not be available for LFC. The slots and ducts must also be inspectable and cleanable periodically. Accessibility to the collector ducts beneath the slots appears to be particularly important because this area would be most susceptible to clogging. The effect of these requirements on the aerodynamic design is such that specifications for slot spacing and sizes must be compatible not only with manufacturability but also with maintainability.

Another maintenance-oriented requirement is that the design should allow the installation of sensing devices to continuously monitor the functioning of the LFC system. Early detection of defective regions would be highly desirable from the standpoint of reliability and efficiency.

Restrictions imposed by practical repairability must also be kept in mind in connection with the aerodynamic design requirements. Thus for example, sufficient allowances should be provided in the suction system design, in terms of slot geometry and pumping capacity, to maintain LFC even under slightly deteriorated surface conditions due to field repairs.

5.1.1.4 LFC Systems Requirements

An LFC airplane will have two unique systems not found in conventional aircraft: (1) a suction system and (2) a leading edge protection and/or cleaning system. The basic requirements for the suction system are to provide enough pumping power to remove the proper amount of boundary layer air from the wing and minimize the losses in the ducting system to the extent practical.

Distribution of the suction airflow is done by appropriate throttling. But the system must operate over a range of conditions and with the minimum amount of energy loss. As a guideline for reducing duct losses, the maximum allowable Mach number should be limited to $M = 0.3$. Propagation of compressor-generated noise through the duct system up to the slots has been noted as a potential problem. Specific noise treatment may be required to avoid this type of adverse interaction.

5.1.2 WING DESIGN

The fundamental concern of the designer of a laminar flow airplane is the aerodynamic design of the wing and the special provisions and systems required to assure essentially full, reliable achievement of laminar flow most of the time under a variety of operating conditions. To meet these objectives, concepts were successfully developed for a basic aerodynamic design of a high-speed wing compatible with laminar flow requirements. The selection of the wing geometry parameters such as sweep, thickness, aspect ratio, and taper ratio was based on preliminary wing optimization studies. For example, these show that the minimum wing weight for $M = 0.8$ cruise occurs for a sweep between 25 deg and 30 deg. Because of concern with crossflow instabilities associated with a swept wing, a sweep of 25 deg was chosen as the maximum tolerable while still avoiding suction in the nose portion of the leading edge. The geometric properties of the wing design are given in Figure 5.1-1.

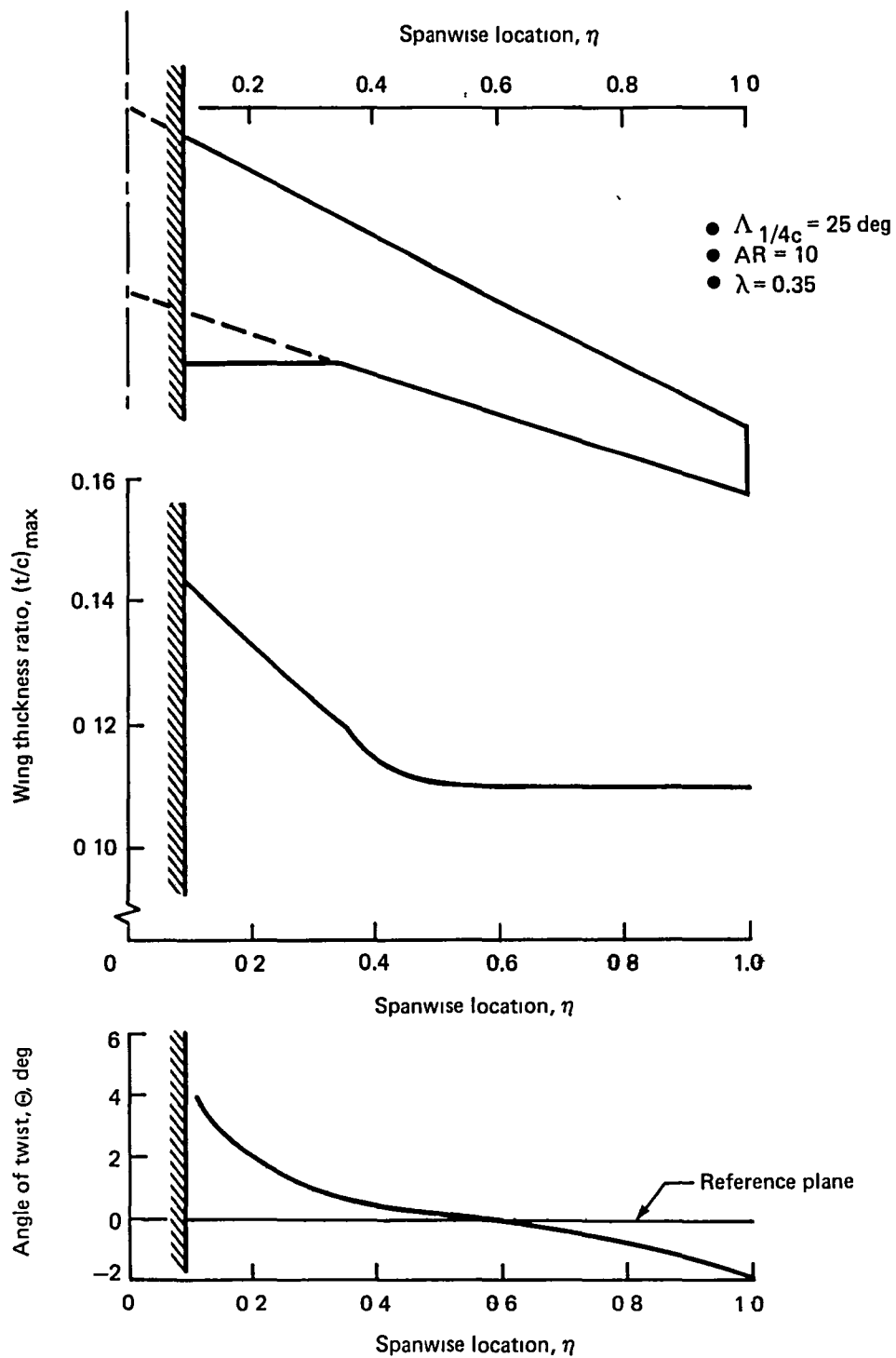


Figure 5.1-1. Principal Wing Geometry Definition—Planform, Thickness and Twist

An advanced technology airfoil section designed specifically for LFC application has been incorporated in the basic wing design. Figure 5.1-2 shows this section as applied to the outboard wing. The inboard sections shown provide the appropriate transition between the outboard portion and the wing root to preserve the desired transonic characteristics and maintain a favorable isobar pattern compatible with LFC. Because of the potential impact of leading edge contamination and premature transition along the attachment line, the relatively blunt nose portions inboard are tailored to provide pressure gradients limiting the growth of $Re_{\theta_{a.l.}}$ to less than 125.

Based on advanced boundary layer stability analysis methods (Refs. 7, 8, 9 and 10), a suitable suction surface has been developed and integrated into the overall wing design. The suction flow distribution is illustrated by Figure 5.1-3 for both design and off-design conditions. The suction slot arrangement to provide these distributions is shown in Figures 5.1-4 and 5.1-5.

5.1.2.3 High-Lift Systems

The principal difference between the high-lift system chosen for the present design and the one that would be used on a contemporary turbulent airplane is the lack of a leading edge device. The compelling reason for this choice was the practical difficulty associated with maintaining laminar flow across a surface discontinuity that would be unavoidable with any movable leading edge device. However, because of the high cruise altitude requirement for an LFC airplane, the resulting lower values of wing loading and thrust loading provide more than adequate takeoff and landing performance. Thus, a leading edge high-lift device is not essential and, in fact, even the trailing edge flap system may be a relatively simple, single-slotted design. Figure 4.0-2 shows the planform arrangement of the high-lift system in relation to the trailing edge control surfaces.

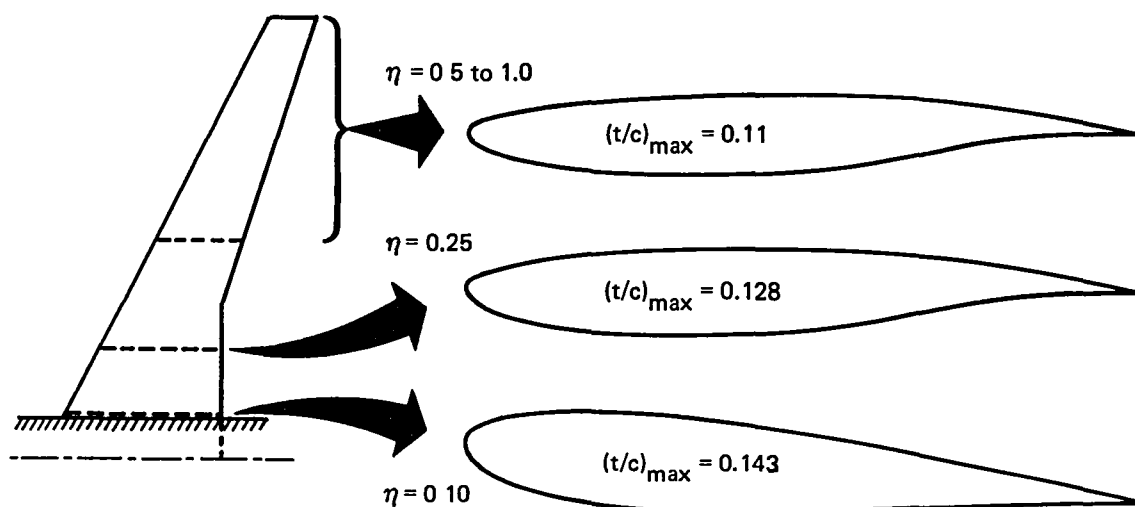


Figure 5.1-2. Representative Airfoil Sections

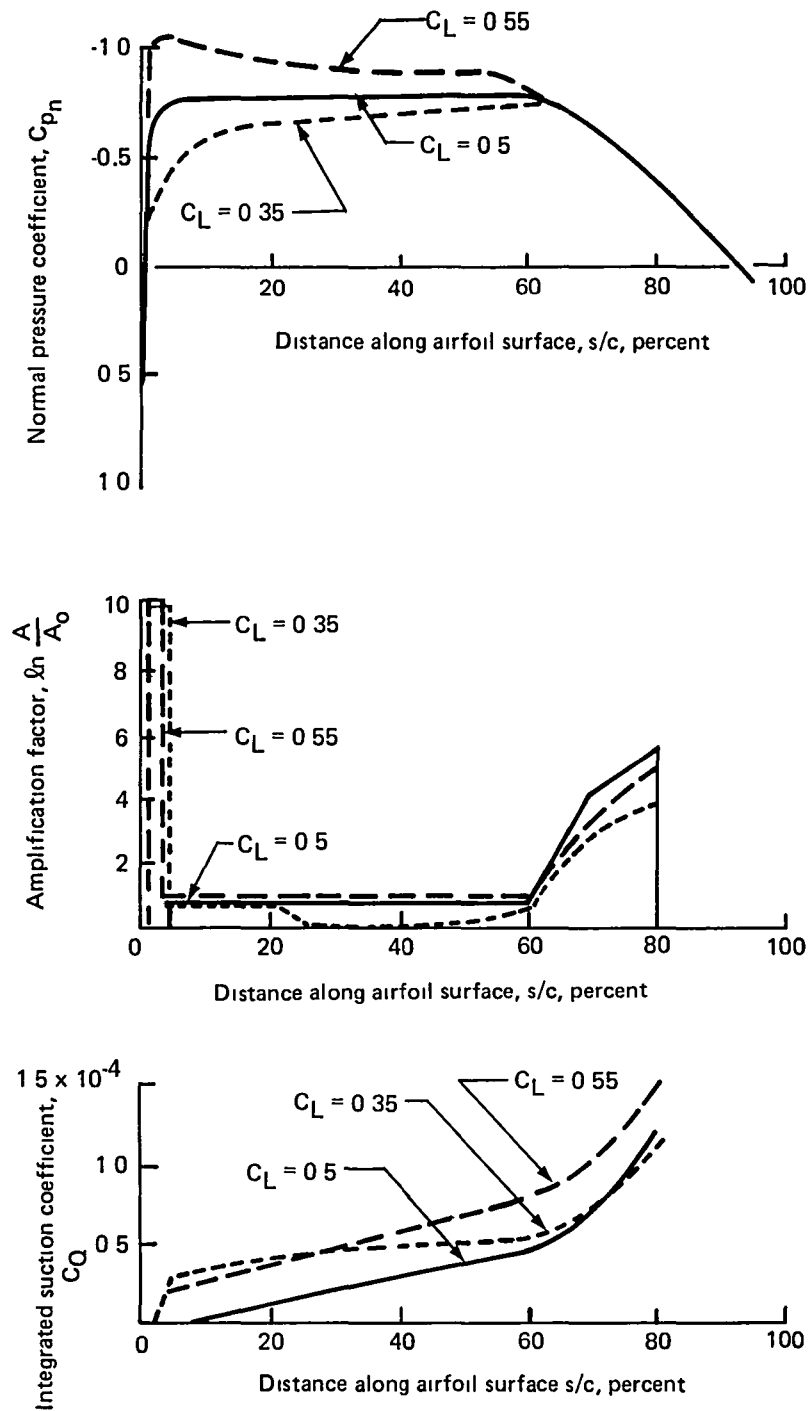


Figure 5.1-3. Off-Design Suction Requirements—Upper Wing Midspan

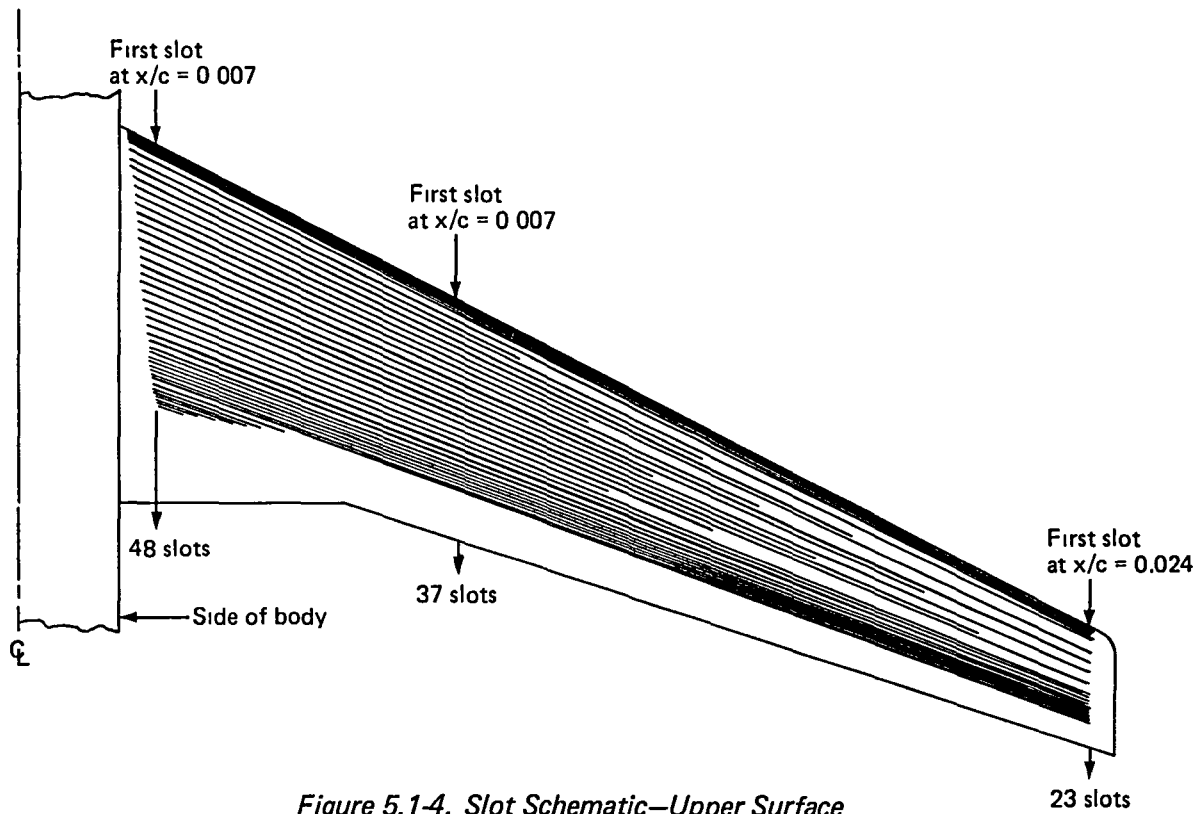


Figure 5.1-4. Slot Schematic—Upper Surface

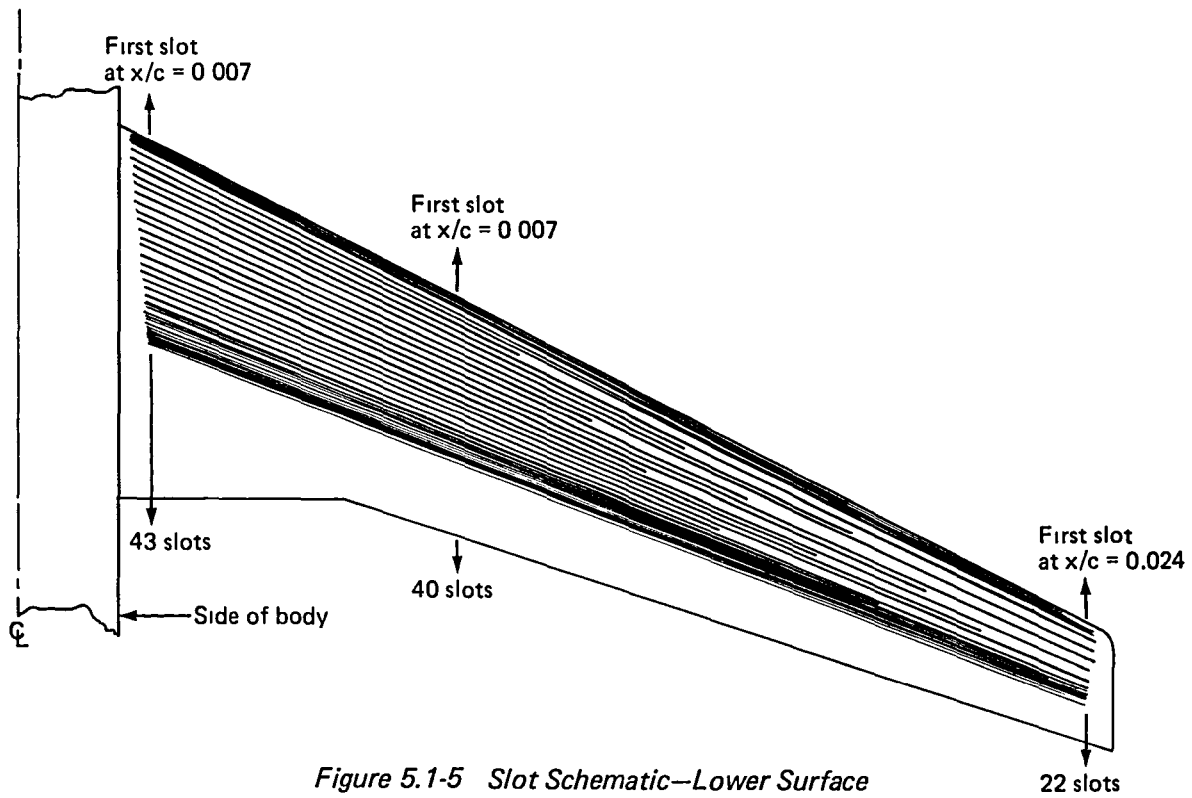


Figure 5.1-5 Slot Schematic—Lower Surface

5.1.2.4 Flight Controls

The lateral control system provided for this airplane is conventional, featuring both ailerons and spoilers. The inboard ailerons are intended for high-speed application to augment the spoilers and provide control redundancy. The outboard aileron is used for low-speed operation only. Ailerons and flaps incorporate the camber adjusting feature for high-speed flight and the inboard aileron is also drooped with flaps (up to 20 deg) at low speeds. The spoilers occupy the same spanwise extent as the flaps. The spoilers also provide flight path control to meet emergency descent requirements.

5.1.3 AERODYNAMIC TEST PROGRAMS

The aerodynamic test program accomplished during the contract was oriented to provide insight into some of the phenomena of controlled laminar boundary layers and to support the critical design decisions. Thus major attention was focused on the validation of the basic aerodynamics of the suction surface design and the investigation of various types of disturbances including noise, as well as the sensitivity of LFC operation to off-design conditions. The test program was carried out in four phases over the contract period as follows:

- a. Model and test setup development.
- b. First test period--validation of the basic model without LFC.
- c. Second test period--validation of the model with LFC.
- d. Third test period--exploration of sensitivities to surface protuberances, off-design pressure distributions, and imposed noise.

5.1.3.1 Wind Tunnel Tests

Figure 5.1-6 shows the layout of the complete test apparatus. The installation included fairings on the tunnel floor and ceiling to prevent significant spanwise pressure gradients on the model. A three-segment trailing edge flap was also used to provide flexibility in pressure distribution adjustments. The model installation permits the changing of incidence angle as well as lateral position by manual adjustments.

Since the most critical area on a swept wing is the leading edge area, the model was constructed to permit laminarization over the first 30% of the chord for the upper surface and the first 15% of chord on the lower surface. The basic model features can be extended to provide full-chord laminar flow.

Typical results are illustrated in Figure 5.1-7, which shows the variation of drag with suction intensity. As expected, the minimum drag is reached when suction is sufficient ($C_q = 0.7 \times 10^{-4}$) to laminarize back to the 30% chord position. Figure 5.1-8 compares the actual suction requirements against levels initially estimated. The agreement is considered quite good when the difference between the wind tunnel test conditions (which included turbulence and noise) and those implicit in the original estimate (i.e., flight conditions) are recognized.

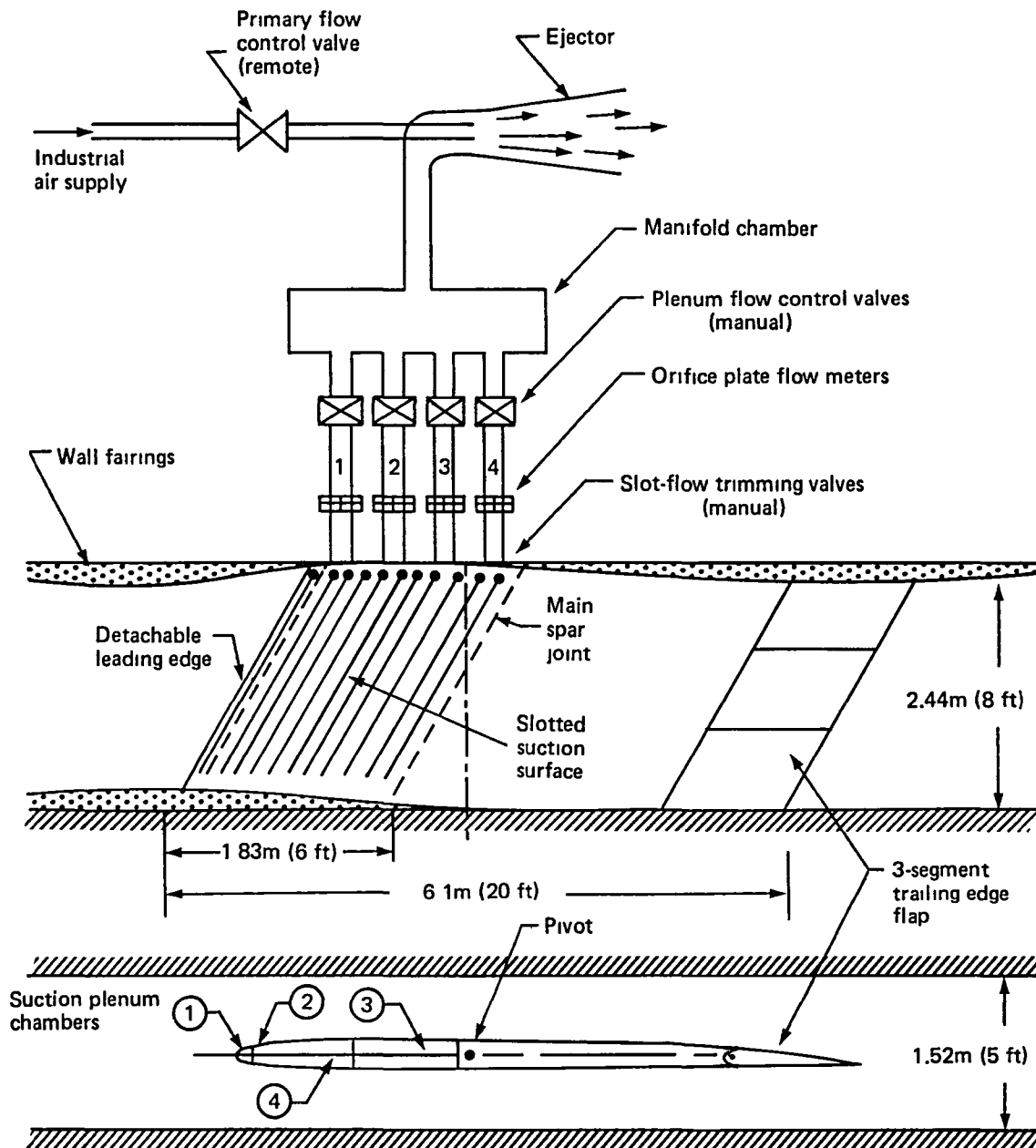


Figure 5.1-6. LFC Test Installation in Boeing Research Wind Tunnel

The results of tests to determine sensitivity to surface protuberances for two- and three-dimensional types are shown in Figures 5.1-9 and 5.1-10, respectively. Although reasonable agreement with previous results in regions of constant pressure seems apparent, the clear implication that laminar flow breakdown is more sensitive to crossflow is new information provided by these tests.

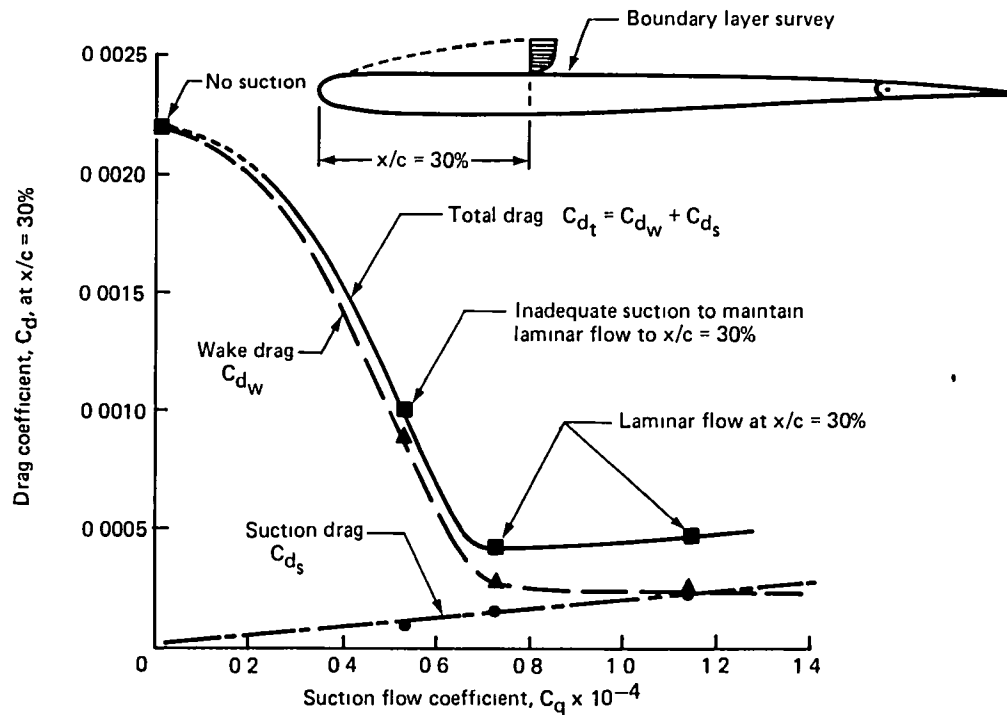


Figure 5.1-7. Variation of Drag With Suction Intensity

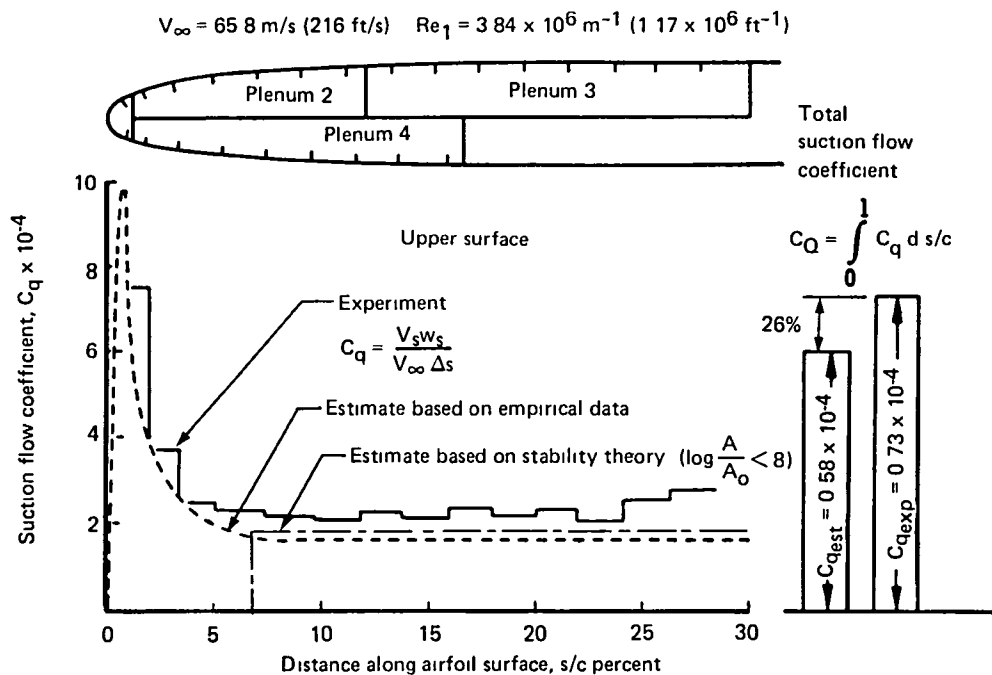


Figure 5.1-8. Estimated and Actual Suction Requirements

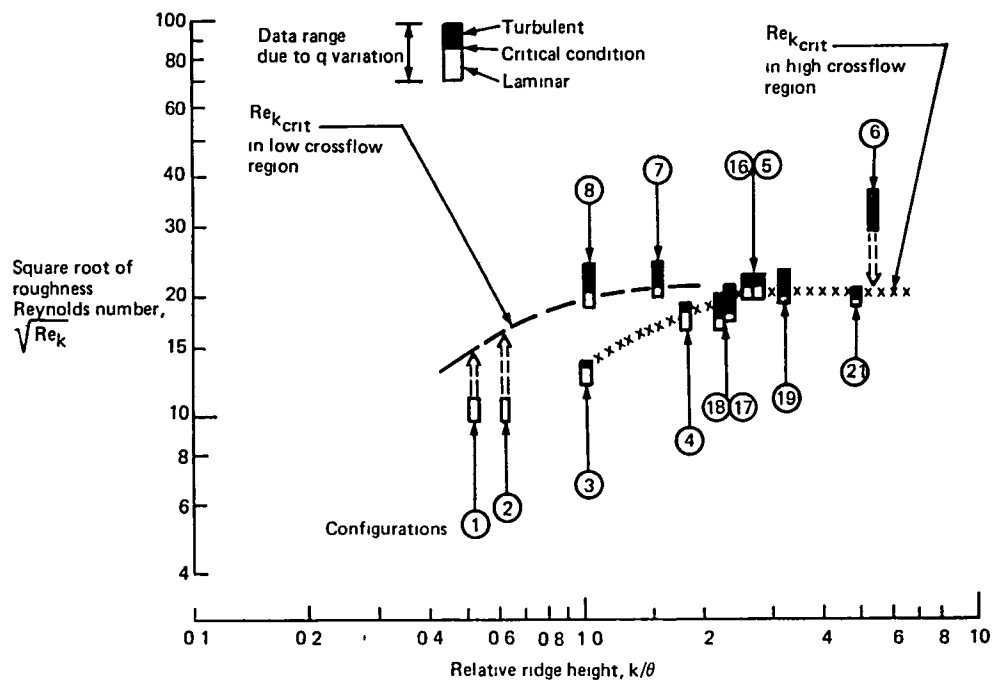


Figure 5.1-9. Summary of Present Results on Critical Roughness Reynolds Number for Two-Dimensional Protuberances

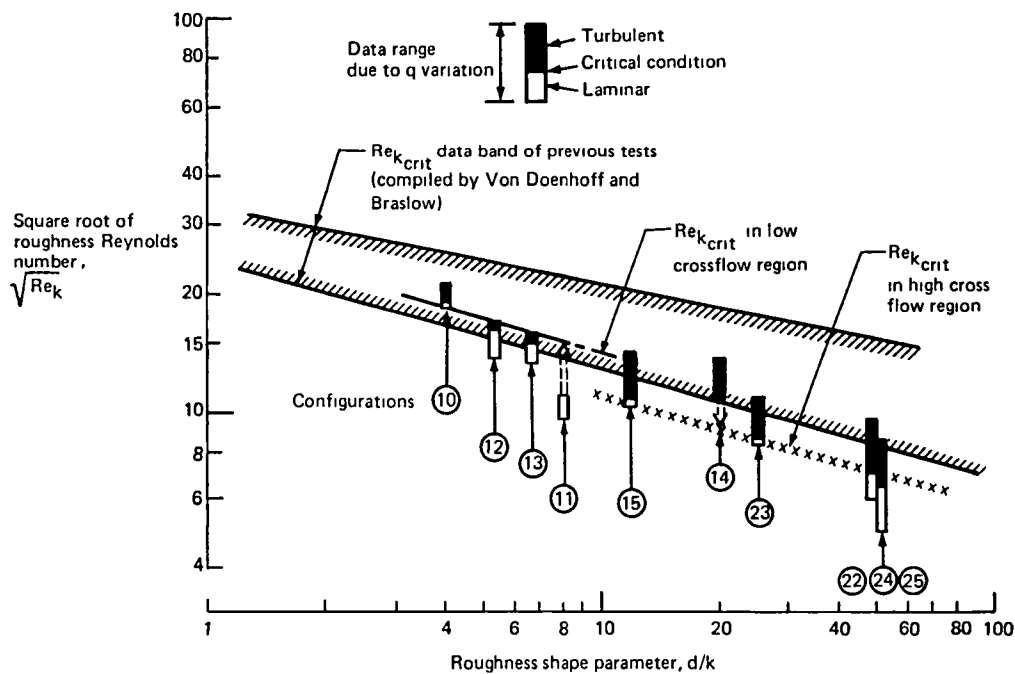


Figure 5.1-10. Comparison of Present Results on Critical Roughness Reynolds Number With Previous Data—Three-Dimensional Protuberances

5.1.3.2 Noise Sensitivity Tests

As part of the wind tunnel study of LFC aerodynamics, the opportunity was taken to acquire some engineering data on the effects of applied noise fields on the stability of a laminar boundary layer with suction. It was also an excellent opportunity to use a well-developed LFC test model to gather information on test procedures, unknowns in the wind tunnel test environment, and measurement techniques needed to conduct more extensive acoustical tests in the future.

The acoustical test setup is illustrated in Figure 5.1-11, which shows the alternative locations of the noise generator and the reference microphone. Microphone and hot-wire measurements of the noise field and the response spectra were taken at selected locations near the laminar flow surface to determine the response of the controlled laminar boundary layer to an applied acoustic field.

Typical hot-wire response spectra are shown in Figure 5.1-12 for three different types of applied noise spectra. As anticipated, the greatest response occurred when the 1/3 octave band incremental acoustic input was in the frequency range corresponding to the critical range for Tollmien-Schlichting disturbances in the boundary layer. The sensitivity of the laminar boundary layer to disturbance frequency is illustrated in Figure 5.1-13, which shows the critical frequency to be about 1.8 kHz.

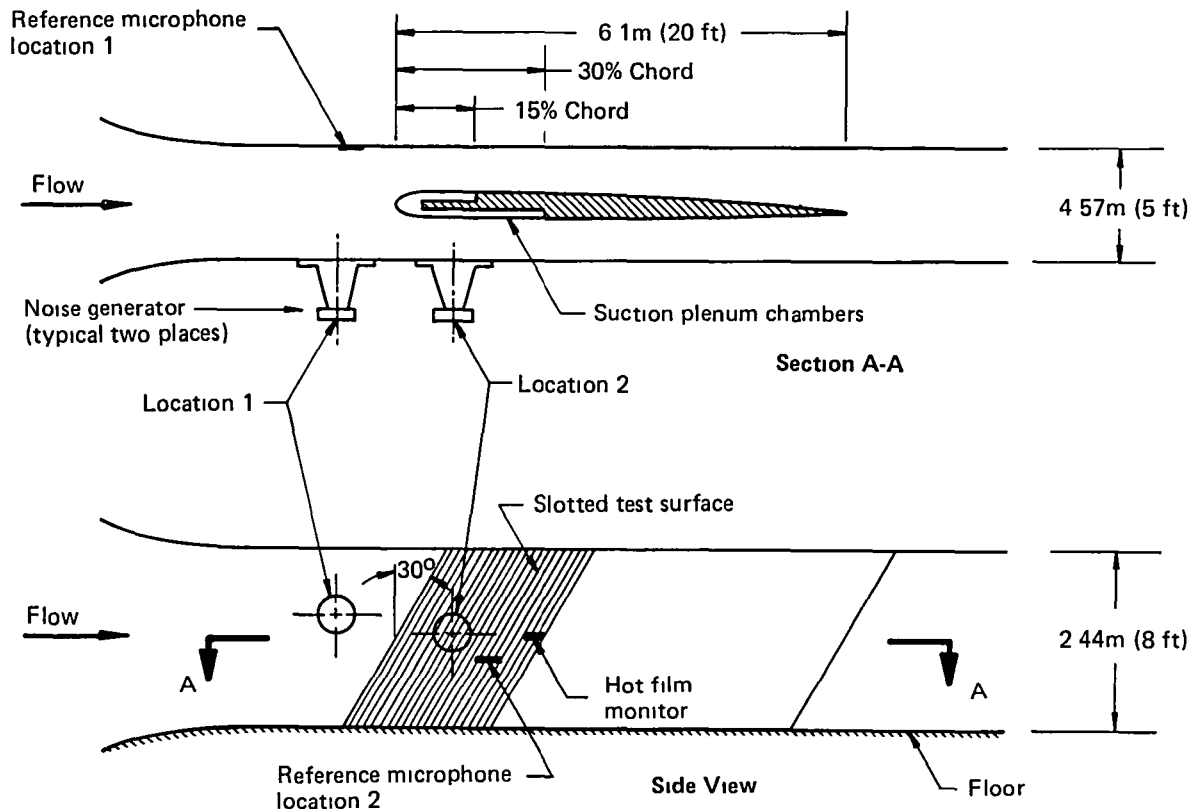


Figure 5.1-11. Test Arrangement for Acoustical Test on LFC Wind Tunnel Model

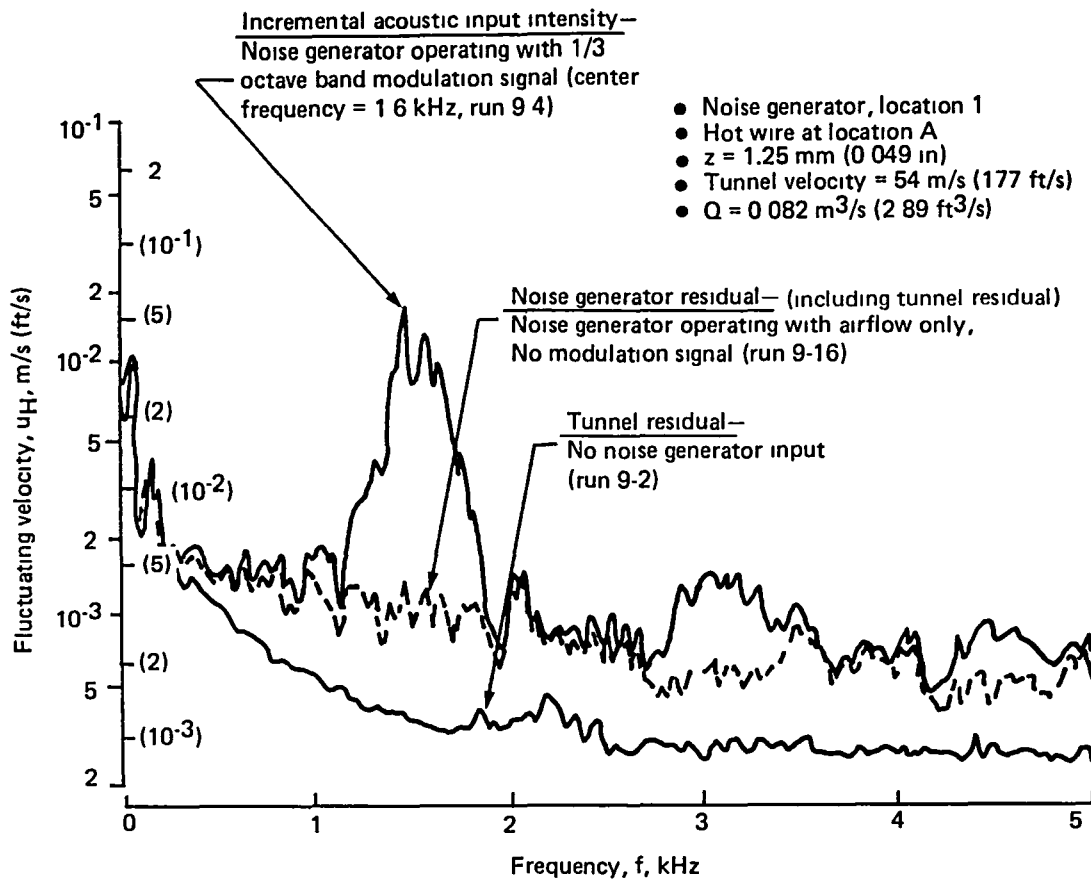


Figure 5.1-12. Hot-Wire Response Spectra—Three Basic Acoustic Conditions

Also, it was found that the allowable level of acoustic disturbance expressed as u_H/U_∞ increased with suction rate as shown in Figure 5.1-14. However, it may be inferred from this data that, beyond some level of disturbance, increasing suction is no longer effective in suppressing transition.

Complete details of the foregoing wind tunnel program including the results of all test phases can be found in References 17, 18, and 19.

5.1.3.3 Suction System Laboratory Tests

The X-21A suction slot geometry concept does not allow for flow adjustment after installation and does not permit access to the internal duct system for inspection and repair. To use this concept on a commercial airplane, it is at least necessary to find a means to facilitate a one-time, as-installed adjustment capability to the suction system flow field area and to allow repair of potential internal duct problems. Studies to achieve this capability identified several candidate geometries. However, before any of these candidates can be seriously considered, their flow characteristics must be determined. This requirement evolved from previous Northrop work, including tests that showed that suction slot velocity

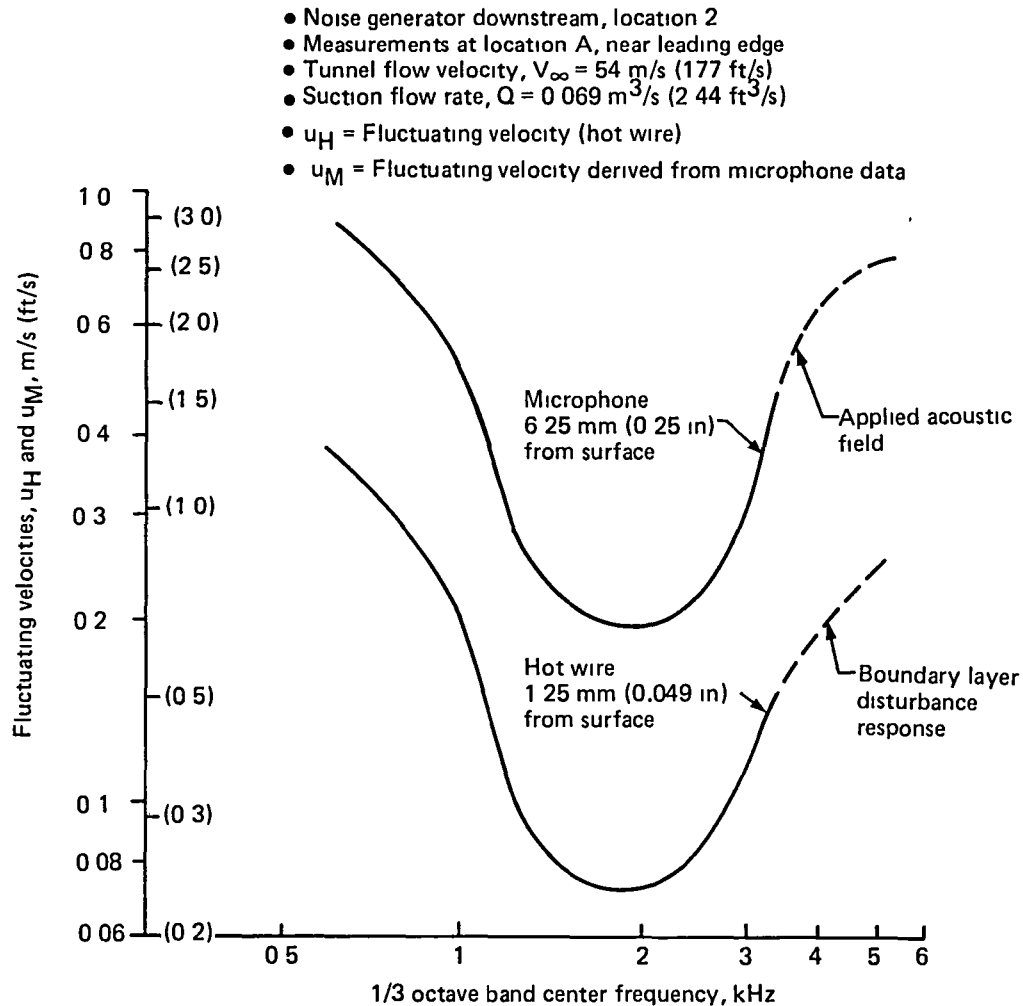


Figure 5.1-13. Critical Incremental Acoustical Velocities Versus Frequency—Hot-Wire and Microphone Sensors

fluctuations caused by internal flow disturbances could propagate back through the slot and cause premature transition of the boundary layer (Ref. 14).

The candidate suction slot geometries differ considerably from the X-21A geometry, and their internal flow characteristics are critical to slot flow stability. These slot geometries were evaluated using a test setup similar to Northrop's in which a hot-wire was used to measure critical flow parameters. Modifications were made to the basic test setup to allow for continuous evaluation of the spanwise slot flow characteristics. The detailed internal arrangement is shown on Figure 5.1-15.

Three basic slot configurations were tested. These consisted of a slot-plenum (three bleed-hole variations), porous aluminum plenum (one density, one porosity) and the X-21A slot plenum (two slot widths). The slot-plenum configurations used a bleed-hole insert to provide a throttling pressure drop for flow control.

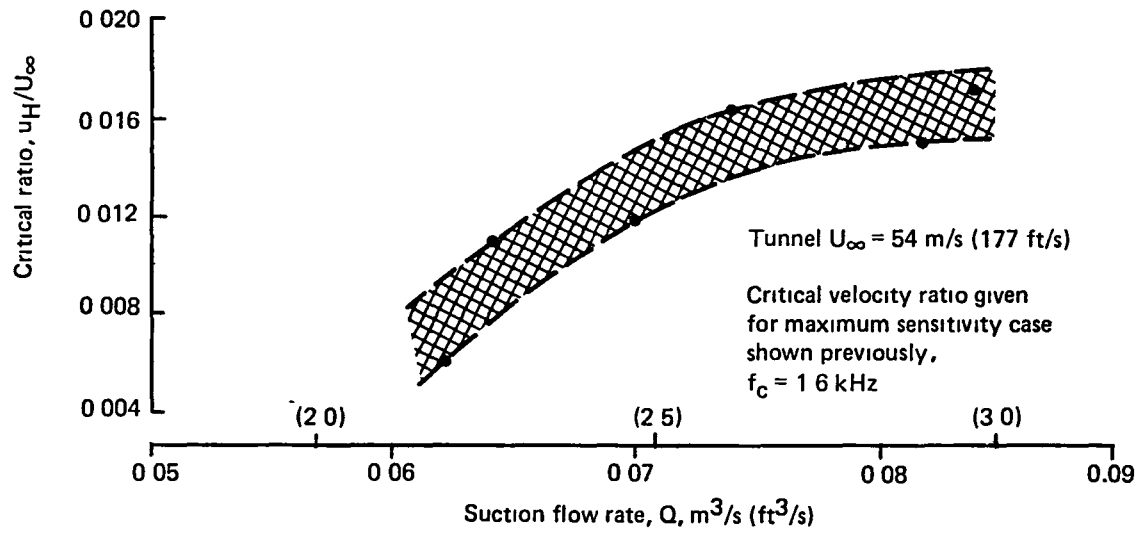


Figure 5.1-14. Variation of Critical Velocity Ratio With Suction Rate at Stable Transition Threshold

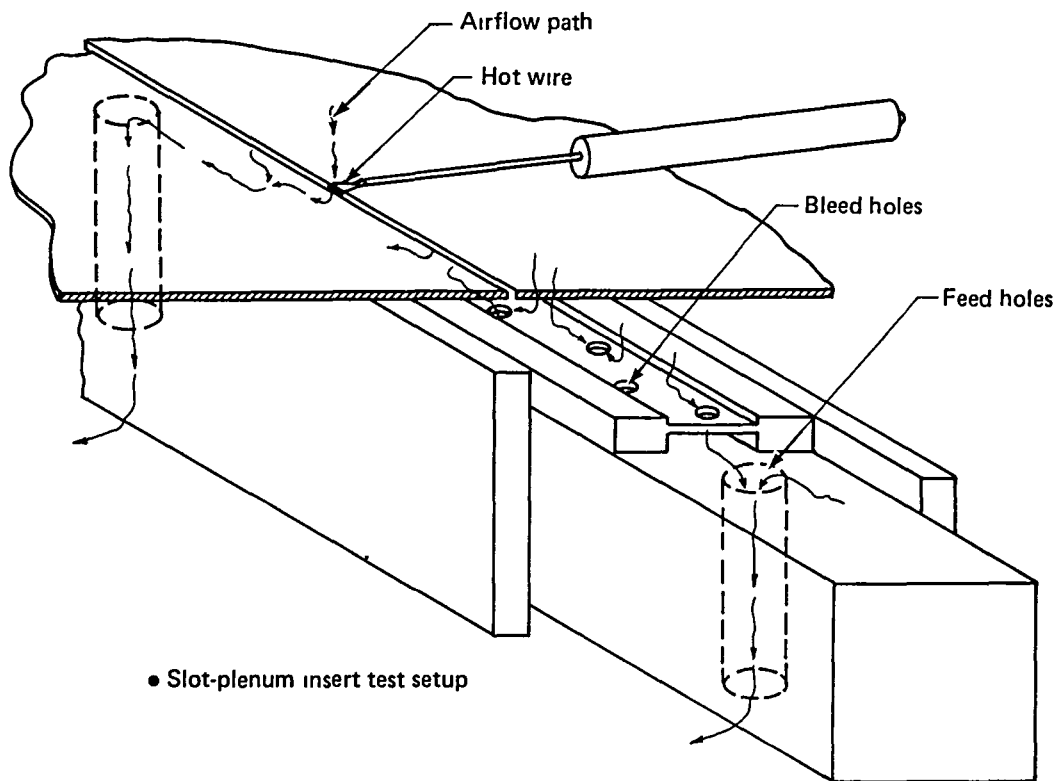


Figure 5.1-15. Test Hardware Arrangement for Slot-Plenum Evaluation

With porous aluminum inserts, the control function could be accomplished through variations in aluminum porosity. The X-21A slot-plenum configuration was representative upstream of the tributary duct flow control elements. The test results are summarized on Figure 5.1-16 and 5.1-17 and reported in detail in Reference 15.

A supplemental test was conducted to determine the clogging characteristics of the porous aluminum plenum configuration. Procedures used were similar to those used under a previously conducted study (Ref. 16) except that the altitude effects were not evaluated. The test results showed that the porous aluminum clogged severely during a 34-day (approximately 2-year equivalent service time) suction test at a representative operating slot Reynolds number of 150.

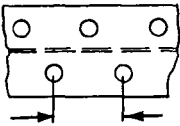
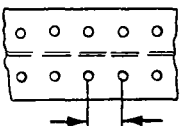
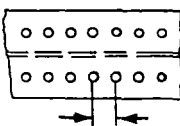
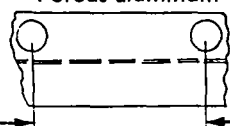
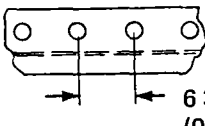
Configuration	Bleed hole diameter mm (in)	Bleed hole area (% of basic)	Velocity variation along slot ($Re_s = 150$) (% of average)
Slot plenum  Basic config + Mod D 7 950 mm (0 313 in)	1 588 (0 0625)	100	± 1.5
 Mod E 3 96 mm (0 157 in)	0 794 (0 0313)	50	± 1.3
 Mod F Mod G 2 007 mm (0.079 in)	0 338 (0 0133)	18	± 1.0
	0 795 (0 0318)	100	± 0.6
Porous aluminum  19 05 mm (0 75 in)	3 175 (0 125)	57	± 7.5
X-21A  6 35 mm (0 25 in)	1 588 (0 0625)	63	± 1.0

Figure 5.1-16. Comparison of Suction Strip Velocity Variation Along the Slot

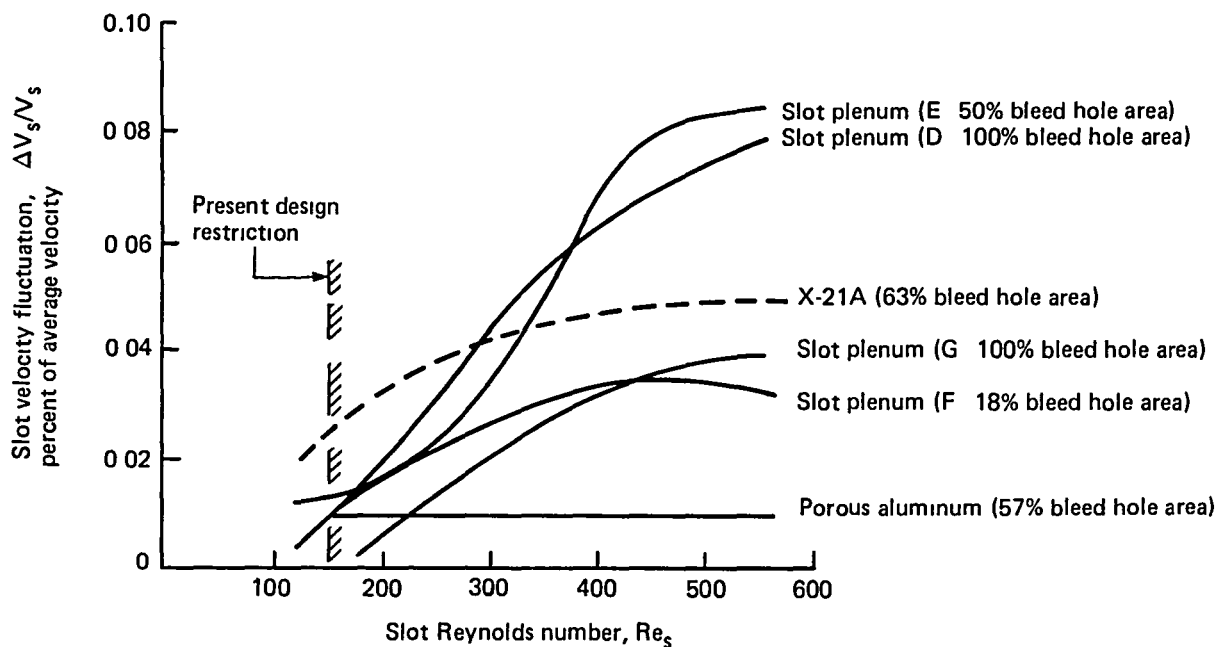


Figure 5.1-17. Suction Strip Slot Velocity Fluctuation Comparison

The conclusions from the test results are summarized as follows:

- All test configurations showed slot velocity fluctuations considerably less than those of the X-21A over the range of Reynolds numbers that would be used for airplane suction system design.
- Velocity variation along the slot would be within the recommended $\pm 1.5\%$ of maximum velocity gradient for all configurations except porous aluminum.
- The slot-plenum configuration bleed holes can be used for slot airflow balancing.
- The use of porous aluminum in the slot-plenums is unacceptable because of severe spanwise slot velocity gradients and excessive clogging characteristics.

5.2 STRUCTURES AND MATERIALS

The structures and materials tasks were arranged to carry out a systematic evaluation of the structural design, materials selection and manufacturing alternatives to arrive at a practical LFC wing and empennage design. Many alternative design concepts using combinations of materials appropriate for each were developed and evaluated before arriving at the most promising design for application to an LFC transport for the 1990 time period.

Selected structural (Ref. 17) and environmental (Ref. 18) tests were accomplished during this period to support the development and evaluation of promising concepts.

5.2.1 DESIGN REQUIREMENTS AND OBJECTIVES

The overall requirement of the structural design was to create a practical wing capable of maintaining laminar flow reliably in a realistic operating environment. The design must conform to existing (or projected) FAA and Boeing requirements for production commercial transport airplanes and the Aerodynamic requirements discussed in Subsection 5.1.1.

The major design objectives were oriented primarily toward minimum weight, production costs, and maintenance costs, while maintaining acceptable operating characteristics.

The above objectives are not totally independent of each other since, in most designs, a strict adherence to one jeopardizes another. The principles associated with the above must all be carefully applied, evaluated, and traded to arrive at the most practical balance for each structural design. Since actual dollar values could not be assigned to represent the degree to which cost objectives were met, relative ratings for each competing design were determined on a judgmental basis largely by assigning relative complexities.

5.2.2 STRUCTURAL CONCEPT AND MATERIALS DEVELOPMENT

Wing geometry, suction requirements and structural loading play major roles in determining the workability of each concept. Thus there was considerable interaction between the development in the structured area and aerodynamic development of the wing geometry. These developments were not necessarily conducted in parallel in all aspects. However, it was necessary to use the same wing and design ground rules on all candidate structural concepts to provide a rational comparison. Therefore, appropriate wing geometries were chosen at different stages of the study to correspond with the then-current state of development. The wing used during the exploration phase had a quarter chord sweep of 25 deg, incorporated an advanced airfoil and had an area of 339 m² (3650 ft²). The developmental phase, about a year later, used the wing most current at its onset. This wing had the same area but the quarter chord sweep was changed to 15 deg and the cross section and the spanwise variation of wing thickness ratio were updated.

Figure 5.2-1 illustrates the distinctly different types of structural concepts developed and evaluated during the exploration phase. The major objective was to examine a wide range of structural concepts and material combinations to identify approaches having a high potential for application to LFC wings. Numerous options were studied and supported by limited structural and environmental tests leading to a selection that would satisfy structural requirements and provide a feasible design to approach minimum weight and cost.

To provide a point of reference, a conventional turbulent wing with standard skin-stringer construction was developed and weighed. The reference wing and all of the above candidates were developed with the same ground rules, design conditions, box geometry, and technology base.

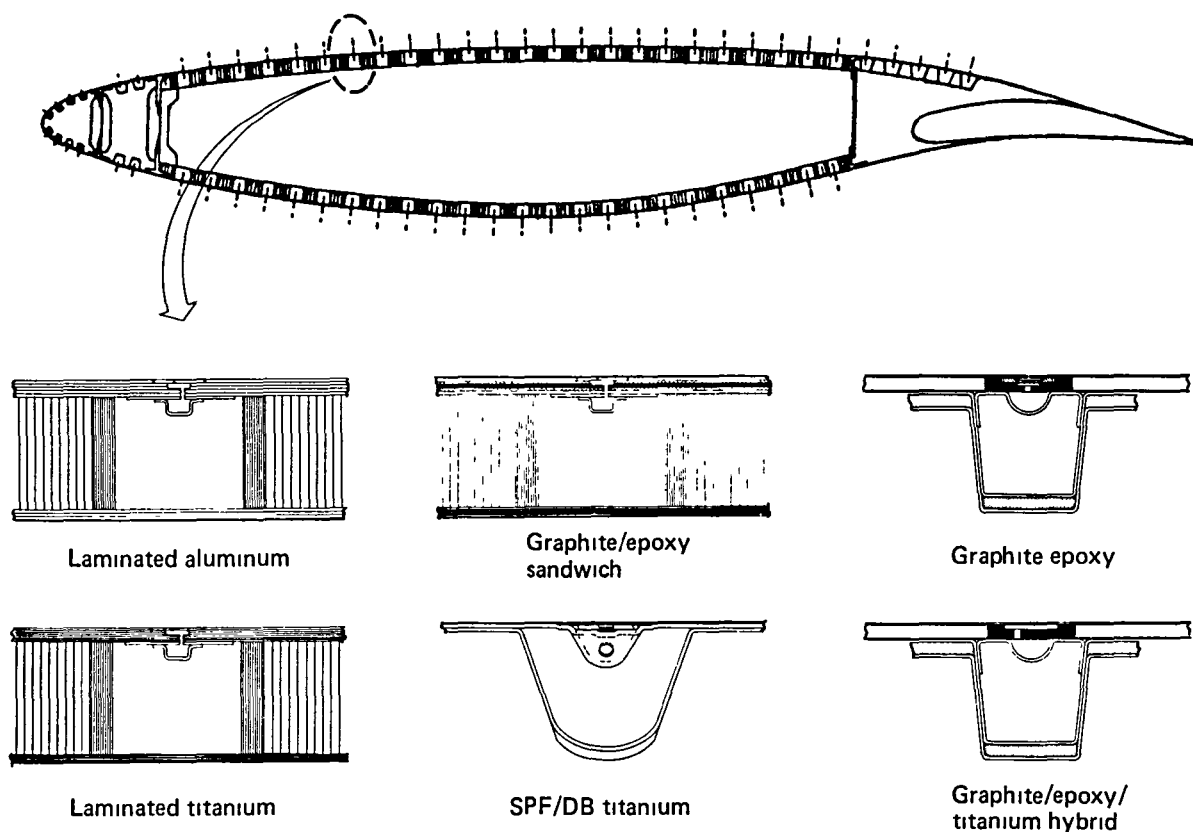


Figure 5.2-1. Structural Concept Candidates—Exploration Phase

Figure 5.2-2 shows a weight comparison of some of the more promising designs which evolved in the exploration phase. Based on this comparison and an evaluation of the relative feasibility of the designs, the laminated aluminum concept was selected for further development as being most likely to be applicable in the near term. While the potential of the graphite/epoxy concepts was clearly recognized, the existence of numerous unknowns and development problems indicated that it would be applicable only in the longer term. Therefore, further work on composites for LFC wings was considered to be unwarranted since successful culmination of the on-going work in the ACEE program would clearly be applicable to the LFC wings.

Work in the developmental phase was devoted primarily to further development of the laminated aluminum concept and a continuing search for more desirable structural arrangements using aluminum. Figure 5.2-3 illustrates the four concepts which survived the evaluation process. These served as a basis for the concept selection for application to the final LFC transport design. A weight comparison of three of the above is shown in Figure 5.2-4. The final weights for the hat-stiffened/fiberglass cover concept were not developed because preliminary estimates indicated it be noncompetitive. Thus, from a weight standpoint, no really







Concept		Structural weight		
		Cover panel, kg (lb)	Upper panel, kg (lb)	Total wing, kg (lb)
Reference		6454 (14 230)	5588 (12 320)	20 797 (45 850)
Concept No 1 Laminated aluminum concept		7135 (15 730)	6209 (13 690)	22 697 (50 040)
Concept No 2 Laminated titanium concept		7888 (17 390)	6650 (14 660)	24 013 (52 940)
Concept No. 3 SPF/DB titanium concept		7800 (17 190)	7071 (15 590)	24 330 (53 640)
Revised concept No 1		7865 (17 340)	6477 (14 280)	23 686 (52 220)
Concept No 4 Graphite/epoxy concept		5905 (13 020)	6241 (13 760)	21 046 (46 400)

Figure 5.2-2. Initial Weight Comparison—25-Deg Wing Sweep

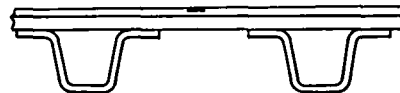
Laminated aluminum
plus honeycomb



Inverted stiffeners plus
fiberglass panel



Hat stiffened plus
fiberglass cover



Conventional plus
fiberglass cover

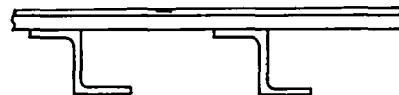


Figure 5.2-3. Structural Concept Candidates Development Phase

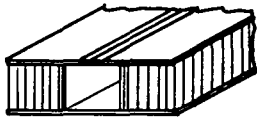
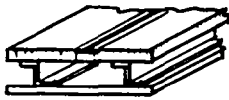

Concept	Laminated aluminum, kg (lb) (Reference LFC wing) 	Inverted stiffeners/fiberglass cover, kg (lb) 	Conventional construction/fiberglass cover, kg (lb) 
Lower panel	8133 (17 930)	7892 (17 400)	7289 (16 070)
Structure	8133 (17 930)	7008 (15 450)	6700 (14 770)
Cover	— —	884 (1950)	589 (1300)
Upper panel	7439 (16 400)	9956 (21 950)	8105 (17 870)
Structure	7439 (16 400)	9072 (20 000)	7475 (16 480)
Cover	— —	884 (1950)	630 (1390)
Total wing	24 980 (55 070)	27 201 (59 970)	24 788 (54 650)

Figure 5.2-4. Final Weight Comparison—15-deg Wing Sweep

important distinction exists between the laminated aluminum plus honeycomb and the conventional construction/fiberglass cover concepts, although the latter appears to have a slight advantage.

5.2.3 SUCTION SURFACE DEVELOPMENT

The surface of a production airplane wing is subjected to many hazards not encountered in laboratory or wind tunnel environments. Foreign object damage is common on conventional airplanes. An LFC airplane wing surface will be more fragile and at the same time the smoothness requirements are much more severe. Because it is obviously impractical to replace an entire surface of a wing every time local damage needs to be repaired, it is apparent that surfaces should have multiple replaceable segments. The development of replaceable suction strips therefore become a requirement. The objectives in design of the suction strips were to provide reasonably rugged, practical designs and to minimize production, maintenance and repair costs.

However, self-cleaning concepts, or designs with moving parts to provide otherwise desirable operating characteristics, were dropped because of cost, complexity and anticipated problems with dependability. Spring-retained or "snap-in" designs proved impractical because wing deflection causes relative movement which tends to put the suction strip out of tolerance. The machining tolerances that would be required for a snap-in design would be impossible to obtain for the entire length of each of the many strips required per aircraft. Six concepts survived initial evaluation; they are shown conceptually in Figure 5.2-5. Each of the arrange-

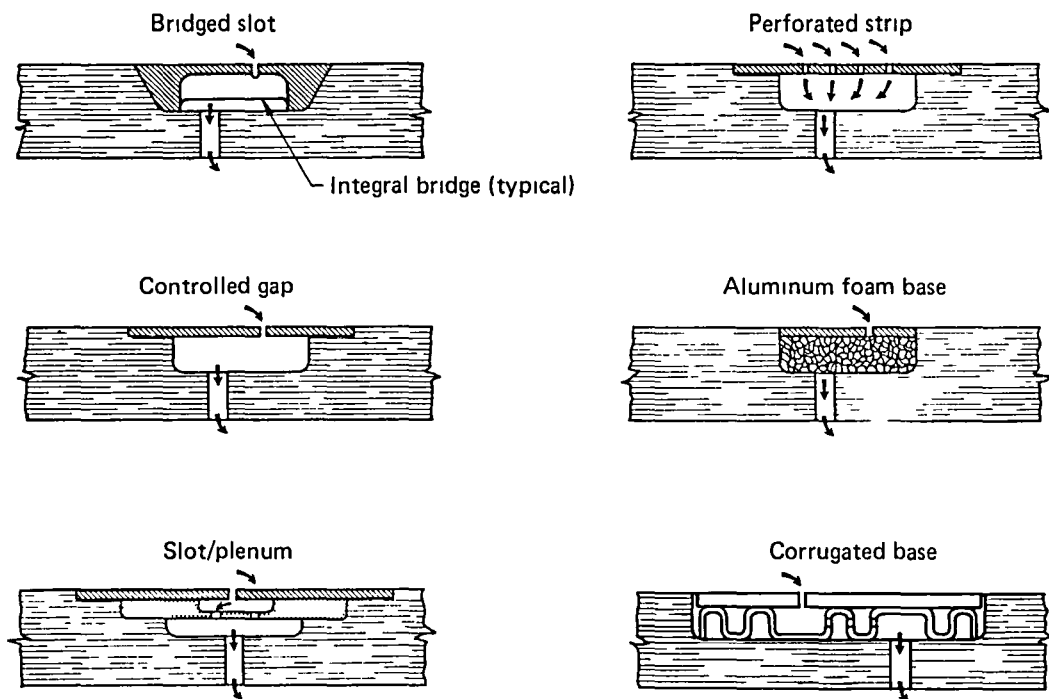


Figure 5.2-5. Suction Insert Candidates

ments shown was considered to warrant investigation and each had particular features of interest as discussed below.

a. Controlled Gap Insert

The controlled gap concept appeared simple and inexpensive. No precision sawing of slots was necessary. In trial installations, two separate pieces were made and bonded to the structure at the proper spacing. In practice, this did not work because the strips tend to move during the bonding operation, leaving the slot width out of tolerance. There may be satisfactory solutions to this problem for production, but no further work was done on this concept.

b. Bridged Slot Insert

The bridged slot concept was designed to overcome the problem of holding the slot width during the bonding operation but retaining the prefabricated unit feature. This concept was far more costly than others discussed here because it required precision chem-milling as well as precision sawing.

Parts made for structural testing utilizing the bridged slot insert had insufficient bond area to attach the insert to the skin. However, a minor design change can be expected to solve this problem. Also, the "bridges" may cause excessive disturbances to the suction airflow, which would require flow test evaluation. No further work was done on this concept following the structural tests.

c. Aluminum Foam Base Insert

The aluminum foam base concept was developed to minimize precision machining and simplify achieving smoothness on installation. It uses "Duocel" foam aluminum as the base or carrier for the slotted strip. A single piece of aluminum and a slightly oversize strip of foam are bonded in the plenum. A hand roller can be used to crush the foam to provide a smooth flush surface. After curing, the slot is then cut in the strip. However, this concept had unsatisfactory air flow characteristics and clogged during flow testing. It was, therefore, considered unsatisfactory and eliminated as a candidate.

d. Corrugated Base Insert

The corrugated base concept was intended to overcome the shortcomings of the aluminum foam design while retaining the "compression on installation" aspect. The outer slot strip is supported by a corrugated, perforated foil. The installation procedure is similar to that of the aluminum foam concept. The corrugations are deformed slightly by a roller to give a smooth, flush surface. The amount of perforation can be varied to give added airflow control. No parts were built so no testing was accomplished on this design.

e. Perforated Strip Insert

The perforated strip concept is the least expensive arrangement of the inserts investigated. The perforations are made by an electron beam (Steigerwald) process. Hole diameter and pattern can be held to a high degree of accuracy and holes can be produced at a rate of 250 per second. This corresponds to a linear production rate that is faster than a slot can be saw-cut. The manufacturing process gives holes that have a natural taper. When the insert is installed with the smaller diameter end up, dirt particles entering the hole do not get jammed inside the hole. The holes can be made in titanium and aluminum but the unfinished holes in aluminum may present a corrosion problem. However, this may be controllable by a process that has been developed to apply primer inside the holes for corrosion control. Primer thickness can be controlled so that, after the primer is applied, the holes are within tolerance.

Preliminary fatigue testing revealed that the fatigue life of the perforated strip failed to meet the goal in highly loaded areas. Cracks initiate at the holes and propagate across the insert. With pliable adhesives, the insert stays in place and this may allow operation for some period without insert replacement. Testing is needed to check airflow characteristics with cracks. The strips are not a safety-of-flight item and are replaceable.

f. Slot-Plenum Insert

The slot-plenum concept incorporates the advantage of the bridged slot, obtains the theoretical advantage of the controlled gap concept and simplifies flow control. Fatigue cracks may develop through the small holes between the two plenums in less than the design life of the airplane, but they

are not flight-critical and will not significantly affect airflow. The inserts are replaceable. This concept has been flow-tested successfully and appears adaptable to any area on the wing.

5.2.4 STRUCTURAL AND ENVIRONMENTAL TESTS

The early portion of the exploration phase revealed the need for limited structural tests using small samples. The purpose of the developmental testing was to identify the severity of the major problems, investigate proposed solutions to the problems, establish design guidelines, and identify areas needing further study so that concept development could proceed in an orderly, efficient manner. Included in the test program were evaluations of structural fatigue using dog-bone specimens, cleaning and clogging characteristics of inserts, water ingestion and freezing and lightning strike effects. The results are not reported herein, but without exception, the final choice of structural concept (including suction insert) was made to be compatible with the test results.

5.2.5 CONCEPT SELECTION

For each of the structural candidates studied in detail, the qualitative requirements and criteria have been met to a level required for final concept selection. While various cost-related factors were considered, no detailed manufacturing cost figures were obtained. Because of this, the manufacturing cost was judged purely on a manufacturing complexity basis.

Thus, the relative cost of the four concepts is implied by the numbers given in Figure 5.2-6. Resolution of questions on maintenance and repair is also judgmental. The candidates were all given numerical ratings relative to four categories, namely: periodic inspection of primary structure, corrosion prevention and repair, isolation and repair of fuel leaks, and repairability of structural damage. The ratings, as shown in Figure 5.2-7 are not all on the same value scale so they cannot be totaled to give a definitive numerical answer. Thus, the final selection was based on structural weight (obtained by analysis) and judgments of the relative risk associated with each concept.

Based on the weight comparisons and the above data, the conventional construction with fiberglass cover has been selected as the best overall choice for a relatively near-term application to an LFC transport and to support construction of







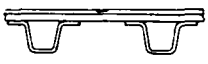
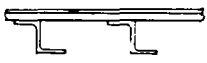
Concepts				
Relative manufacturing complexity	100% Baseline	140%	160%	80%

Figure 5 2-6. Structural Concept Selection—Cost Comparison

Concept				
Periodic inspection of primary structure	3	4	2	1
Corrosion prevention and repair	4	4	2	2
Isolation of fuel leaks	2	2	4	4
Repairability of structural damage	4	3	2	1

● Judgmental comparisons The lower the number, the less detrimental to maintainability

Figure 5.2-7. Structure Concept Selection—Maintenance and Repair Evaluation

a validator aircraft in the 1985 time period. The concept has the potential of being used with new structural materials as they develop. For near-term application, though, it uses familiar materials and requires only the final development of inspection techniques to provide a low-cost workable design adaptable to existing production processes. In the final analysis, the advantage in cost, maintenance, and repairability of the conventional construction with fiberglass cover and the difficulties of incorporating the latest suction requirements into the laminated aluminum concept resulted in the selection of the above concept for application to the final LFC transport configuration presented in Section 6.5

5.2.6 SELECTED CONCEPT DEFINITION

The following discussion briefly presents the features and characteristics of the selected structural arrangement. Reference 19 provides a complete set of design data for the selected concept. Figure 5.2-8 illustrates the concept in its essential form. The wing box is designed and constructed in an entirely conventional manner. The suction surface and the integrated collector duct system is superimposed on the basic wing structure in the form of a glove. This consists of a foam-filled fiberglass sandwich outer skin bonded to a spanwise array of hard foam spacers which have previously been bonded to the wing box. Slot-plenum inserts (or a similar type) are bonded into machined channels in the fiberglass glove.

Figure 5.2-9 shows a crosssection of the wing illustrating the chordwise airflow paths and the allocation of suction air to the five trunk ducts. The suction surface detail and the internal ducting arrangement are illustrated in Figure 5.2-10.

The suction airflow, after passing through a slot, is first collected in a shallow groove called the slot-plenum; from there, it passes into another plenum (i.e., subplenum) via a pattern of bleed holes in the lower part of the insert. This provides the throttling stage. From the subplenum another row of bleed holes transmits the suction air into the chordwise collector ducts. The chordwise ducts then feed into the main trunk ducts which run along the span ahead of and behind the structural wing box.

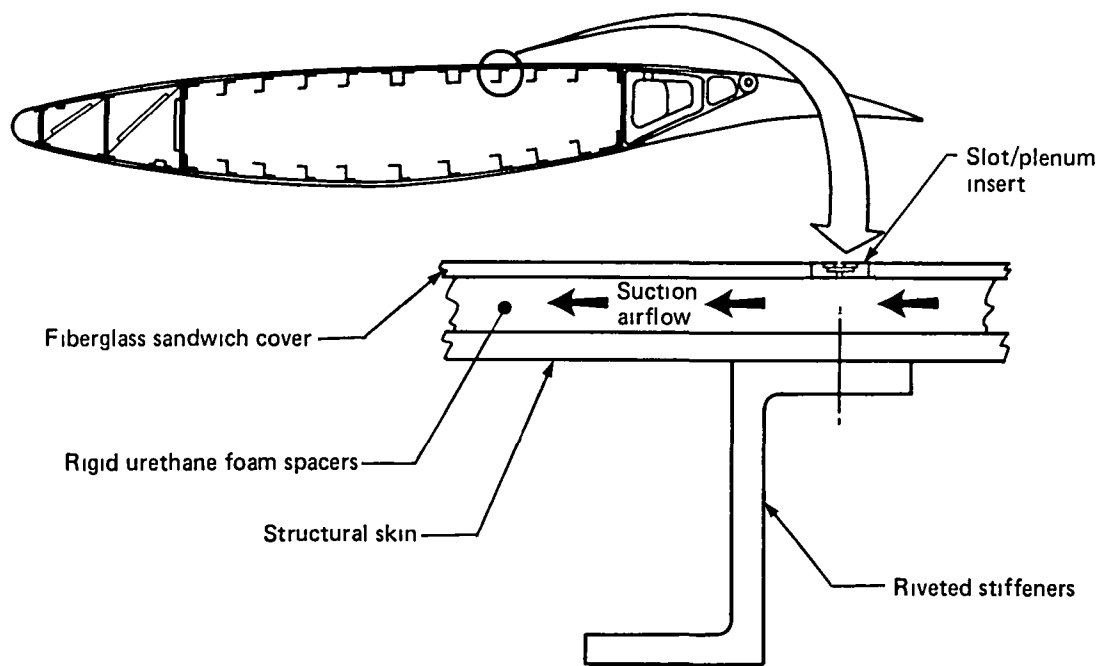


Figure 5.2-8. Conventional Construction/Fiberglass Cover Concept

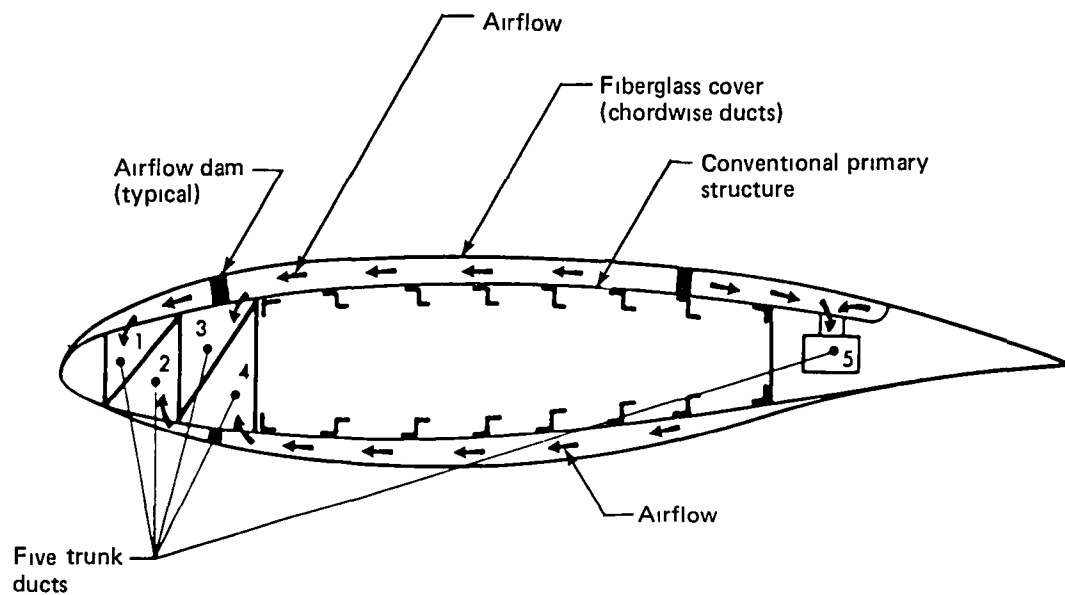


Figure 5.2-9. Conventional Construction/Fiberglass Cover Concept (Five-Duct Configuration)

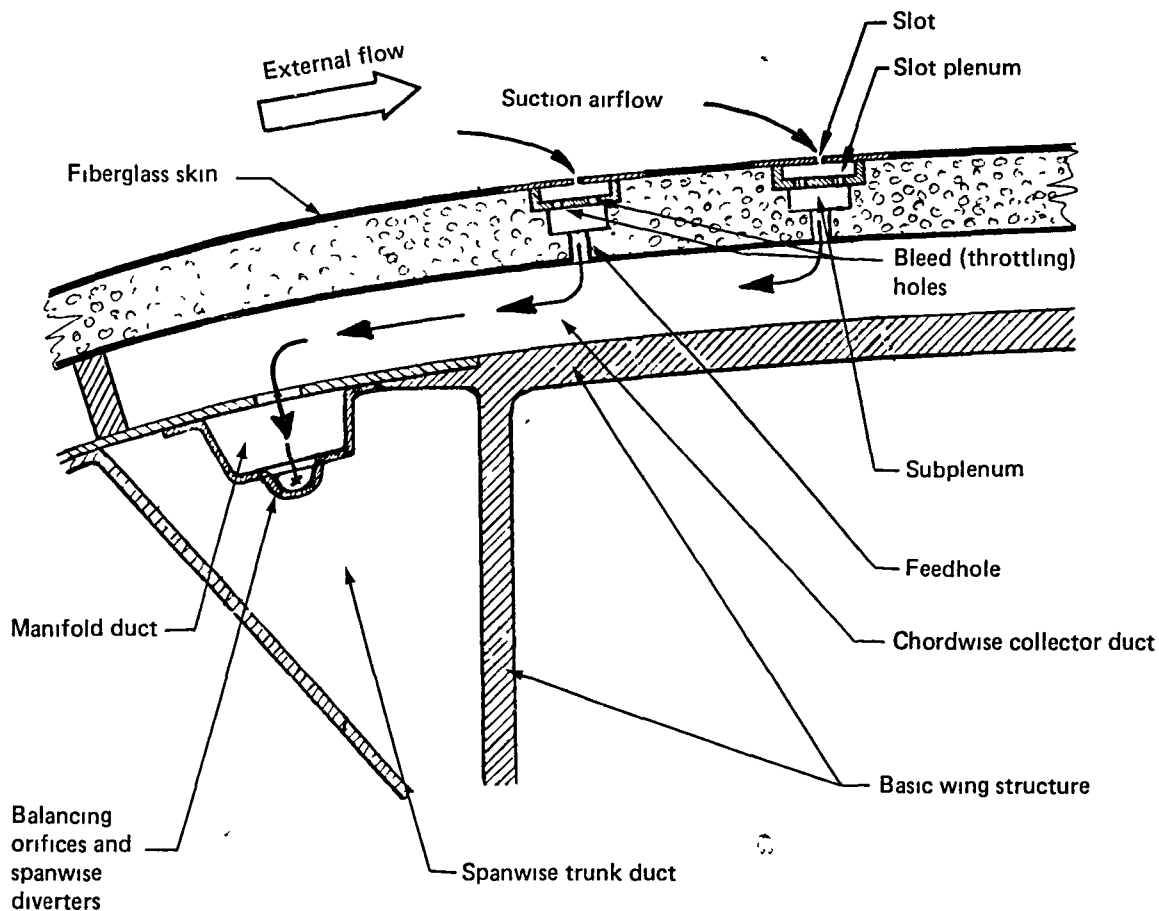


Figure 5.2-10. Suction Surface and Internal Duct System Concept

An intermediate manifold duct, located inside the trunk duct, contains a row of louvers. The louvers direct the suction flow spanwise and provide just enough throttling to offset the pressure gradient in the trunk duct. Each trunk duct has a control valve upstream of the suction pump. This allows adequate inflight adjustment of the suction flow distribution to accommodate off-design operation. The spanwise flow paths in the trunk ducts and the collection system leading to the suction units are shown in Figure 5.2-11. Only the trunk ducts serving the upper surface of the wing are shown, although the two ducts serving the lower surface also feed into the flow collection system.

The leading edge assembly consists of an upper and lower panel, duct separators, the auxiliary front spar, and nose assembly. Figure 5.2-12 illustrates the structural arrangement. The upper and lower panels are fiberglass and urethane foam sandwich panels of which the outer surface is similar to that of the outer panel over the wing box. The core of the panel is made from strips of self-skinning urethane foam; the inner skin is five plies of fiberglass. The duct separators and the auxiliary front spar are bonded aluminum honeycomb to give smooth surfaces to the trunk ducts.

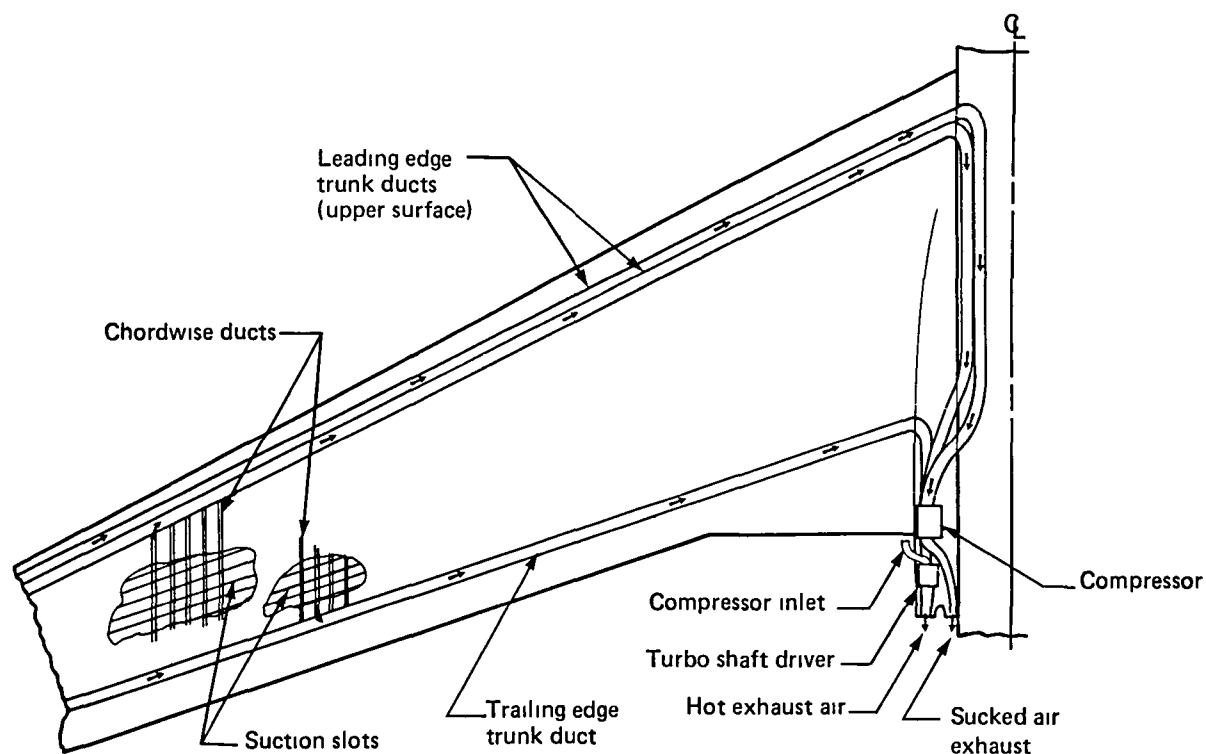


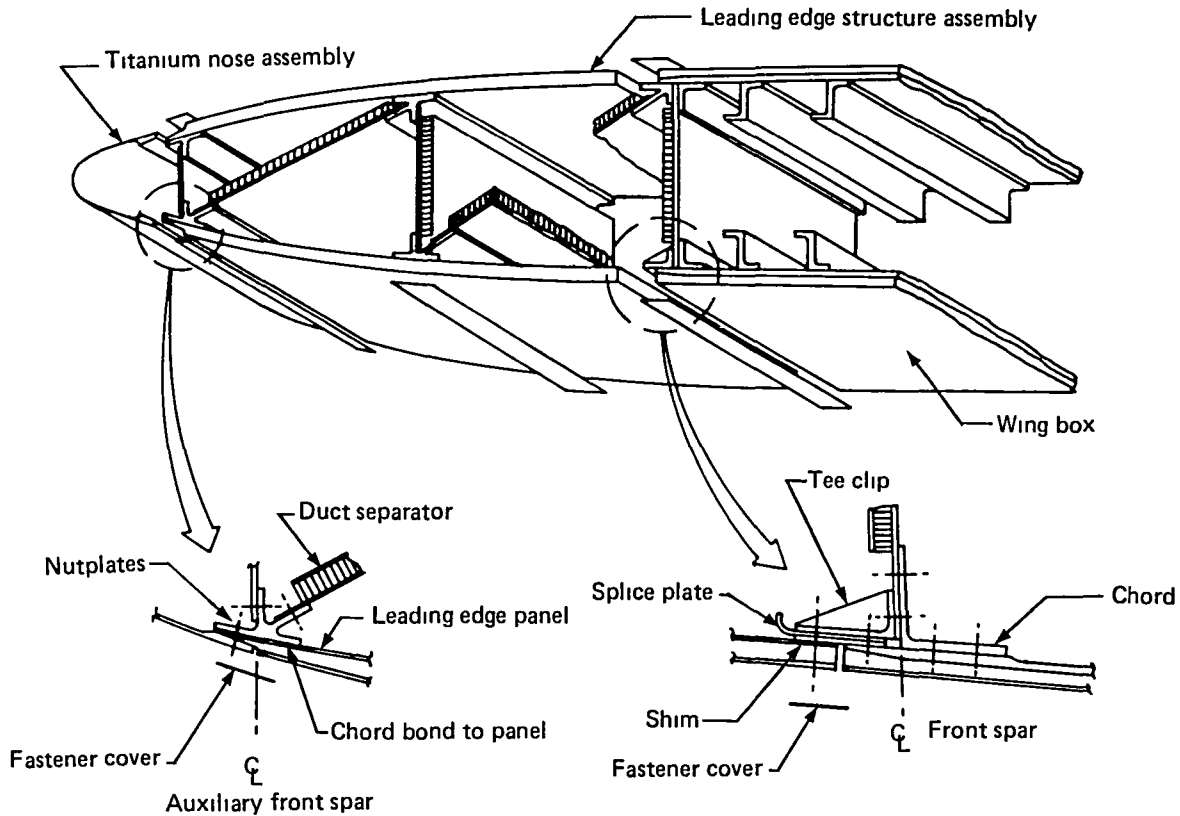
Figure 5.2-11 Conventional Structure—Air Collection System Schematic

The nose assembly is shown in Figure 5.2-13. The nose skin is made of titanium for good erosion resistance and is manufactured in 6.1 m (20-ft) lengths. It is designed to be readily removable for ease of maintenance and repair.

Although no final selection of leading edge systems has been made, a candidate system is illustrated in Figure 5.2-13. The leading edge contains the ducting and flow passages to accommodate the combination of anti-icing, frosting, and suction systems.

5.2.6.1 Environmental Protection

Water can be expected to enter the suction system at some time during airplane operation although the greatest exposure is expected on the ground. While tests have demonstrated that no structural problems will exist from freezing, a drainage system is provided. Drainage for the chordwise ducts of the upper wing surface is accomplished by locating entry holes to the trunk ducts at the lowest points of the chordwise ducts. That this can be done is apparent from Figure 5.2-9. The current arrangement has a dam at 65% chord which is a flow-restrictor type that allows water to drain to the rear trunk duct and still maintain the required airflow distribution at the suction surface. Overboard drains for the trunk ducts are located near the wing tip and at the side of body outside of the laminarized areas. The wing lower surface requires no special drainage provisions in the chordwise



**Figure 5 2-12. Leading Edge Structure Assembly Sequence for Conventional Structure/
Fiberglass Cover Concept**

ducts. The trunk ducts for lower surface air have the same drainage provisions as those for the upper surface air. Check valves at each drainage point prevent air inflow during operation of the LFC system.

Corrosion inside the wing box will present no new problems. The external surface of the wing structural skin will be treated per BAC 5555 (a Boeing surface preparation process) before spacers are bonded in place and will be coated with Corrogard after the spacers are installed. This is the same finish that is now used inside the air conditioning ram air ducts on the 727 airplane and no corrosion has been detected in these areas since this type of protective system was introduced. However, the presence of corrosion, if it should occur, can be detected by nondestructive testing long before it becomes structurally critical.

The wing is not likely to be struck by lightning except at the tips, so that the laminarized portion of the wing is in a low-probability zone. The wing tips are not laminarized and their surfaces are aluminum. The metal suction strips are grounded to the tip and at the side of body to minimize the possibility of damage to the suction surface.

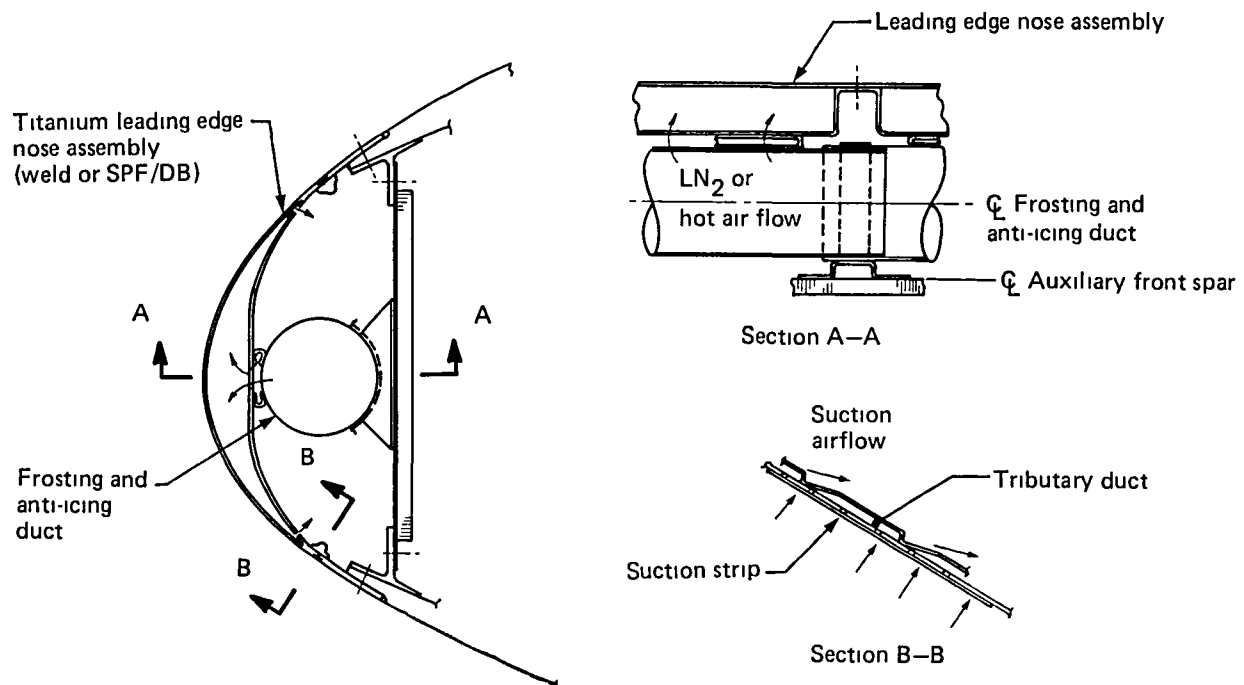


Figure 5.2-13. Leading Edge Nose Assembly

5.2.6.2 Maintenance and Repair

Airplanes incorporating LFC capability would be substantially more difficult to inspect, maintain, and repair than a conventional turbulent airplane. The conventional construction with fiberglass cover concept minimizes many of these problems.

Routine maintenance inspections are normally conducted to locate structural cracks, corrosion, erosion, fuel leaks, and system leaks, and most of the procedures would be applicable for an LFC airplane. Typical wing damage to current commercial aircraft consists of the following:

- a. Cracks (fatigue and stress corrosion)
- b. Corrosion
- c. Ground incidents (collision with service vehicles, other aircraft, and fixed objects while towing)
- d. Jacking incidents (puncture or scoring)
- e. Engine rupture (puncture by flying parts)
- f. Falling objects

- g. Bird strikes
- h. Lightning strikes (puncture and etching)
- i. Hail damage (inflight and on the ground)
- j. Tire tread separation (puncture and denting)

It is estimated on the basis of extensive service experience that cracks and corrosion repair account for 90 % of the structural repair work on the wing. Repair of cracks in the primary structure of an LFC wing would be accomplished in essentially the same manner as for a turbulent airplane except for the removal and replacement of portions of the outer glove and foam spacers. Figure 5.2-14 illustrates a repair procedure for the spacers and outer panel when damage is in an area of high strain and is large in size. The cover and spacers would be cut away to permit repair of the aluminum structure. Following repair, the spacers would be replaced. Either urethane foam or foam aluminum can be used. Using foam aluminum may be easier as it can be crushed to the proper thickness. The premade repair panel would then be bonded in place. Epoxy filler and sanding to contour would be used to smooth out any mismatch. The groove would then be machined to receive a replacement segment of the suction strip. Small repair

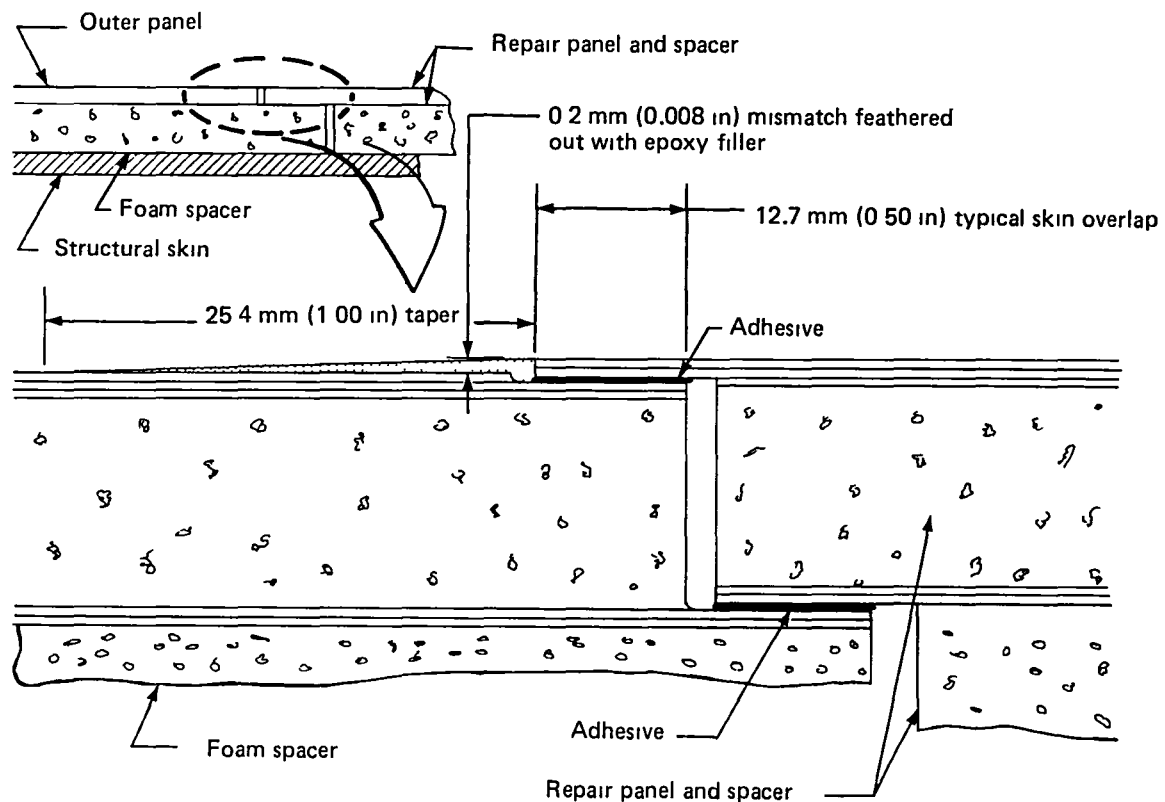


Figure 5.2-14. Cover Repair Scheme

areas and areas in regions of low wing strain would not require the overlap of the cover; a simple butt joint repair would suffice.

Many forms of damage can occur to the outer surface of an LFC wing and no historical data is available to evaluate the extent and frequency of damage to be expected. New operating procedures will be required to minimize damage to the wing surfaces from such things as fueling hoses, dropping tools, walking on the wings, hail, and snow removal.

5.2.6.3 Manufacturing Requirements

The current manufacturing plan is to fabricate and paint complete wing box assemblies prior to wing-body joining. All wing LFC features will be incorporated in the manufacturing sequence prior to the painting operation. The exterior surfaces of the LFC wing box differ from conventional wings in that these surfaces are phosphoric acid anodized to enhance integrity of subsequent bonding operations. To attain the surface regularity necessary to support laminar flow, the wing covers must be laid-up as a single part. While this poses formidable problems in tooling and assembly, it appears to be the manufacturing approach with the greatest probability of success. The covers will have their outer surfaces laid up against a caul plate contoured to airfoil surface shape. Spacer strips, bonded to the outer surface and machined prior to assembling the outer skin, become the tolerance payoff members. The manufacturing process is illustrated in Figure 5.2.15 which shows the essential operations and performance sequence.

5.2.7 HORIZONTAL TAIL DESIGN

Application of LFC to the empennage was not considered in detail until a structural concept for the wing had been selected. The decision was made to use a concept similar to the wing in virtually all respects except for the structural box. Conventional skin-stringer construction for the horizontal stabilizer is not suitable for LFC because the lightly-loaded skin is normally allowed to buckle at low loads. Adding thickness to the skin to prevent buckling imposes a substantial weight penalty, so aluminum honeycomb was selected for the basic structure. The suction surface, leading edge, and trailing edge designs closely parallel those of the wing design.

5.3 SUCTION PUMP AND PROPULSION SYSTEM

The selection and definition of the suction pump system and its location in the airplane was accomplished through a series of component analyses and trade studies. The main propulsion engine was selected on the basis of the expected technology level for the 1990 time period. It will have an engine cycle determined to be near-optimum for an LFC airplane, based on a separate trade study.

5.3.1 DESIGN REQUIREMENTS AND OBJECTIVES

The main propulsion engines do not have a direct impact on the feasibility and operation of the LFC system; hence, the design requirements and objectives for the main engines were based on the airplane thrust requirements and technology level expected in the 1990 time period. Also, the selected engine bypass ratio was desired to be near-optimum for this particular airplane.

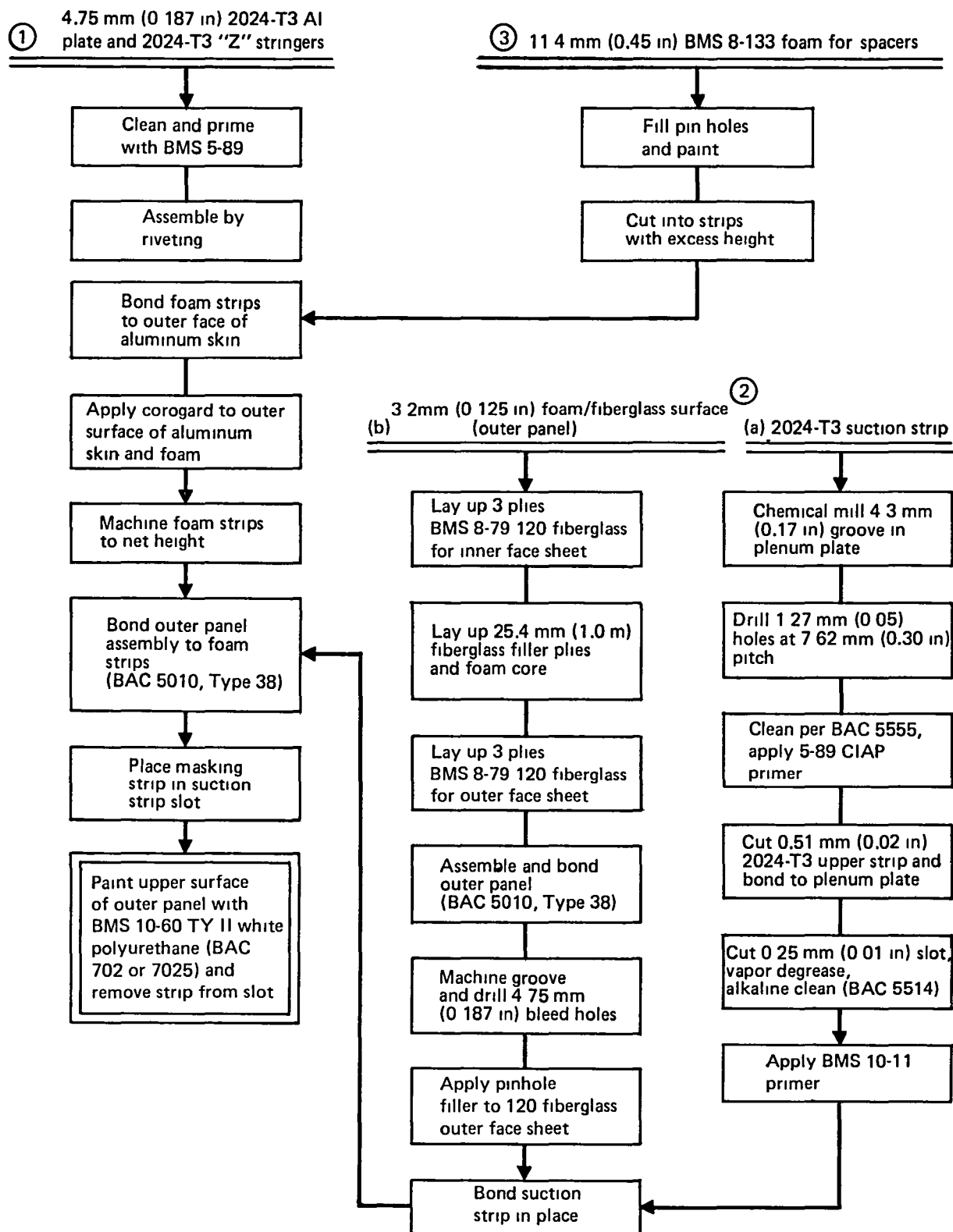


Figure 5.2-15. Manufacturing Sequence for LFC Surface Assembly

The design requirements for the suction pump system were aimed at providing sufficient suction power at all flight conditions within the flight envelope while maintaining acceptable reliability, maintainability and flight safety characteristics.

5.3.2 MAIN PROPULSION SYSTEM

The laminar flow control (LFC) airplane studies and energy efficient engine studies which are both part of the NASA-sponsored Aircraft Energy Efficiency (ACEE) program are parallel efforts aimed at early 1990 entry into service. Thus, for the LFC airplane, it is appropriate that the main propulsion engine be consistent with an engine evolving from the Energy Efficient Engine (EEE) program.

Since the LFC airplane studies began prior to the EEE definition, it was necessary to select a study engine that could be considered representative of an EEE baseline engine. Because of Boeing participation in continuing cycle studies by Pratt & Whitney of engines incorporating advanced technology, it was decided to use the P&W STF-482 study engine for the LFC airplane baseline configuration. This engine has the following nominal cycle characteristics:

Overall pressure ratio	40
Fan pressure ratio	1.65
Bypass ratio	7.5
Maximum combustor exit temperature, °C (°F)	1532 (2700)

5.3.3 SUCTION PUMP SYSTEM

The interface between the duct system and the suction pump system is defined to be at the face of the suction compressors. The design of the suction duct system is presented in the full contractor's report and will not be discussed here. However, it is important to note that the ducting system is separated into low-pressure and high-pressure elements corresponding to the upper and lower wing surfaces, respectively. A summary of ducting system losses is provided in Table 5.3-1 to provide some insight into their impact on pressure ratio requirements for the suction compressor.

The suction pump system consists of coupled low-pressure and high-pressure compressors and the pump drive system. Two separate suction units are required to provide the desired suction airflow and pressure ratios at an initial cruise altitude condition of Mach 0.8 at 12 800m (42 000 ft), for the baseline airplane (see Table 6.0-4). The suction pump system must remove sufficient air from the wing surfaces to satisfy the boundary layer stability requirements over the slotted portions of the wing surfaces within the principal operating envelope. While the system will not normally operate below the operating envelope, it is assumed that system operation can be initiated prior to takeoff and continue until commitment to landing. Operation of the system is also expected during checkout, maintenance, and special situations on the ground.

Table 5.3-1. Internal Duct System Pressure Losses

Duct section	Loss* (%)
Slot/plenum/bleed holes/subplenum	5
Collector duct (chordwise)	2 to 5
Trunk duct (spanwise)	10
Manifold to compressor	5
Compressor to overboard discharge	5
Overboard discharge	As required for discharge velocity equal to free stream

*Percent of free-stream dynamic pressure

5.3.3.1 System Drive Options

Power to drive the suction compressor is available from: (1) the main propulsion engine or, (2) a separate power source in the form of a turboshaft engine. For this study, the alternatives selected for final evaluation were:

- a. Turboshaft engine (OPR = 20)
- b. Bleed-burn or bleed-drive turbine (bleed PR = 10; TIT = 1700°F)
- c. Direct mechanical drive (2-engine system)

The Model 767-807 baseline airplane was configured with the suction pumps located on the wing trailing edge at the wing break. It had been concluded that, with this configuration, the only practical drive method was a separate turboshaft engine. Therefore, to evaluate all of the above alternative drive methods and to provide information on alternative suction unit locations, an aft lower body location was selected for study purposes. In this location the suction system ducting back to the interface point is identical for all drive methods, thus permitting an evaluation of the suction unit independent of the duct system. Figures 5.3-1, 5.3-2 and 5.3-3 show typical arrangements for the drive options with the suction units below the cabin floor level in an unpressurized compartment in the aftbody area.

Safety considerations were an important element in the process of evaluating the operational suitability of alternative suction systems. Safety is influenced by both system drive and unit location. Containment of fragments in the event of rotating machinery failure is a firm requirement for all suction unit locations although some installations are more sensitive than others. Of primary concern is the possibility, even though remote, that fuel or fuel vapors could be present in air entering the suction pump. This could come about through failure (e.g., structural cracks,

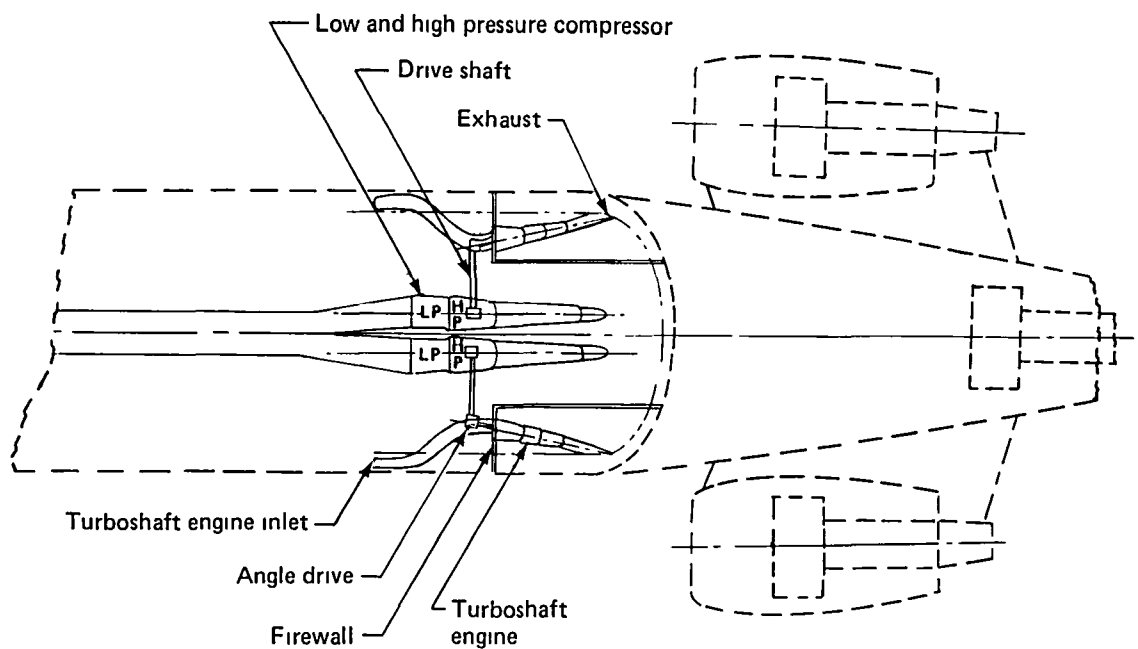


Figure 5.3-1. Turboshaft Engine Drive

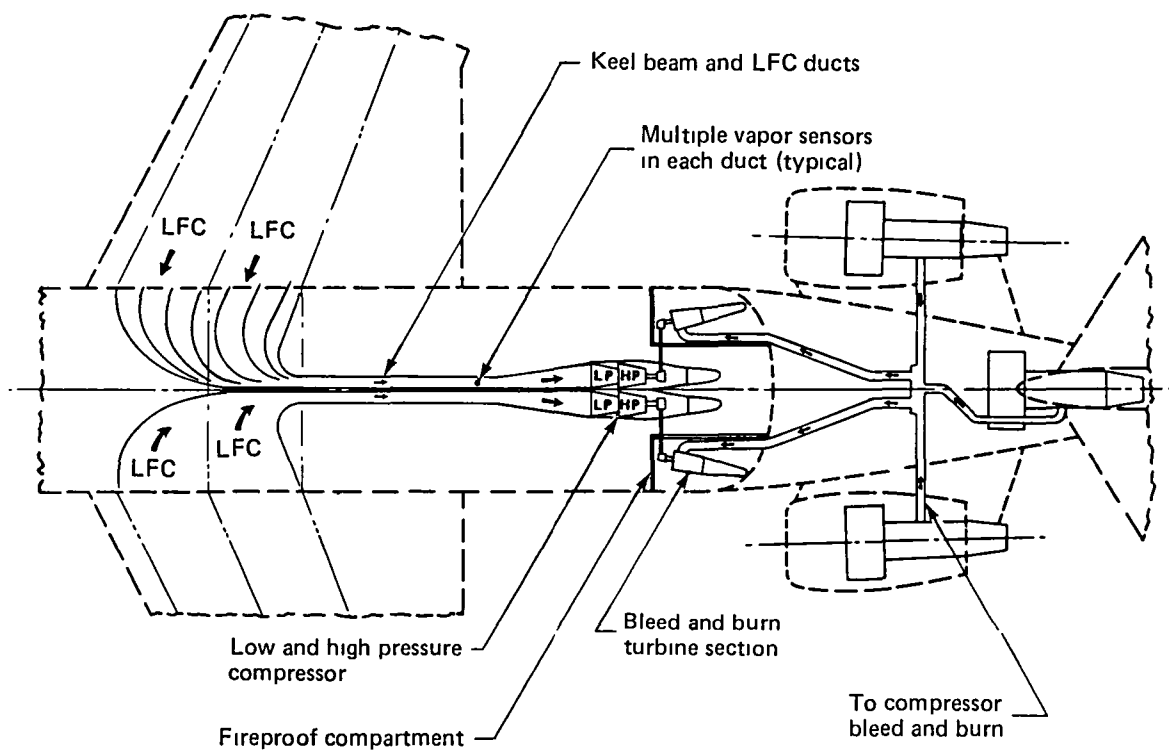


Figure 5.3-2. Bleed and Burn Turbine Drive

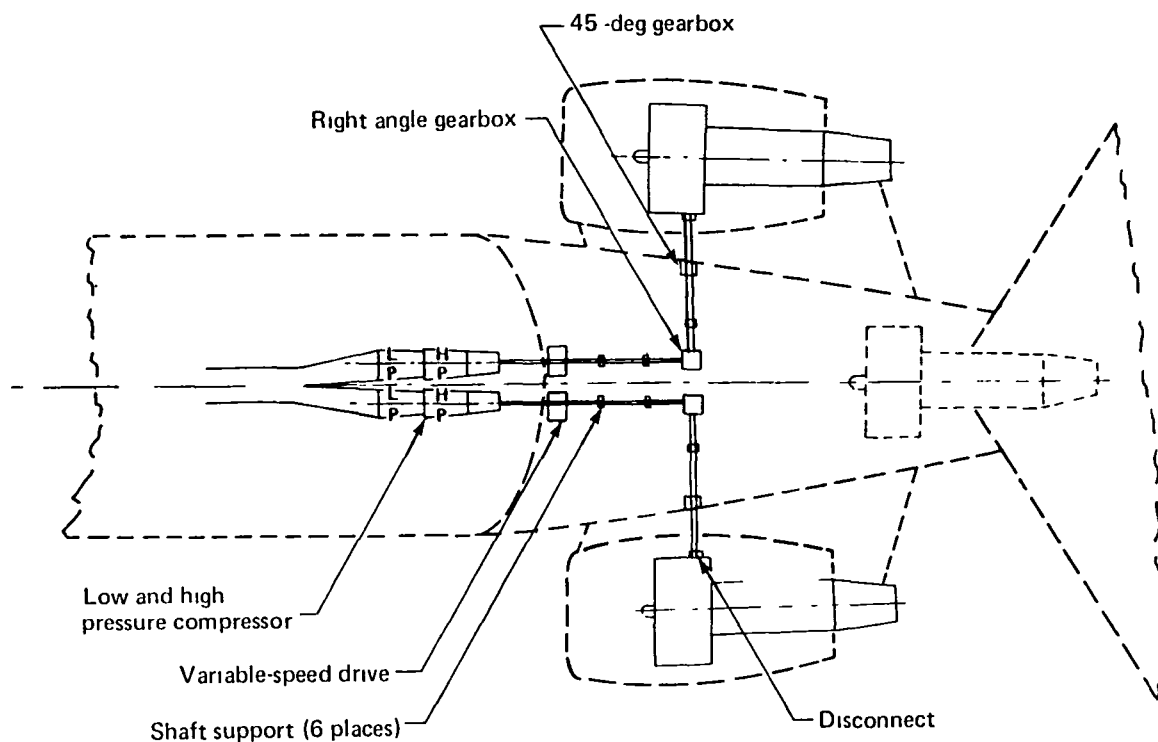


Figure 5.3-3. Direct Mechanical Drive

sealant loss) at the interfaces between fuel tanks and suction ducting within the wing. Thus, to provide adequate safety it would be necessary to install multiple fuel and vapor sensors in the suction system ducting upstream of the compressor faces where a signal from any sensor would trigger an automatic system shut-down. In addition, bearing failure and over temperature sensors would be required on any bearing or gearbox located in the path of the suction airflow. A signal from these sensors would also result in automatic system shutdown.

Further study showed that safety considerations were more demanding for suction units located in the aftbody areas. Additional design requirements included the provisions that all units be shock-mounted to minimize noise transmission and that all rotating equipment be fully contained in the event of a failure. Proper orientation of nozzle exhausts and compartment fireproofing was also given special attention.

The results of the study of drive alternatives have shown that, of the practical options considered, all provided competitive fuel consumption performance (within 1%), whereas the weight advantage was significant for the turboshaft drive. Based on the qualitative considerations discussed above and also a) reliability, b) maintainability, c) ease of control, and d) location and interface flexibility, the advantage was also clearly with the turboshaft drive. Table 5.3-2 shows a comparison of the three drive options based on the above factors. The turboshaft drive option, therefore, was selected as the basis for further design studies and ultimately, for the final LFC airplane configuration.

Table 5.3-2. Evaluation and Selection Basis—Compressor Drive

Item	Aft body location		
	Turbo-shaft	Bleed and burn	Direct mechanical, 2 engines
Net fuel consumption at design point, kg/h (lb/h)	Base	+30 (+66) +0 7%	−18 6 (−41) −0 5%
System weight, kg (lb)	Base	376 5 (+830)	186 (+410)
Reliability and maintainability	High	Medium	Low
Ease of control for off-design operation	High	Medium	Low
Flexibility of interface with other airplane systems	High	Medium	Low
Location flexibility	High	Low	Low

5.3.3.2 Suction Unit Location

Since the results of the drive alternatives study clearly indicated a selection of the separate turboshaft drive, the development of suction unit location options was based on the above choice. Furthermore, Boeing IR&D studies had also shown that the turboshaft drive was the only practical alternative for the baseline configuration with wing-mounted suction units. Thus, the suction unit location study was based on a common turboshaft drive system and an evaluation was conducted for four different locations, three mounted on the wing and one in the aftbody. The wing locations considered are illustrated in Figure 5.3-4.

The two configurations at the wing break both posed structural problems associated with removal of the suction air and routing to the suction pumps. Also, both configurations have significant drag penalties from lost wing laminarized area and basic aerodynamic interference associated with the presence of the suction unit pod. In addition, the aft-spar mounted configuration poses a potential wing flutter problem which would result in increased wing weight. Thus, the wing root location appeared to provide the most workable configuration of the three wing locations studied.

In the final analysis, a number of factors including system weight, maintenance, and safety favored a wing location over the body location. Therefore, the wing root was selected as the best location for the suction pump system.

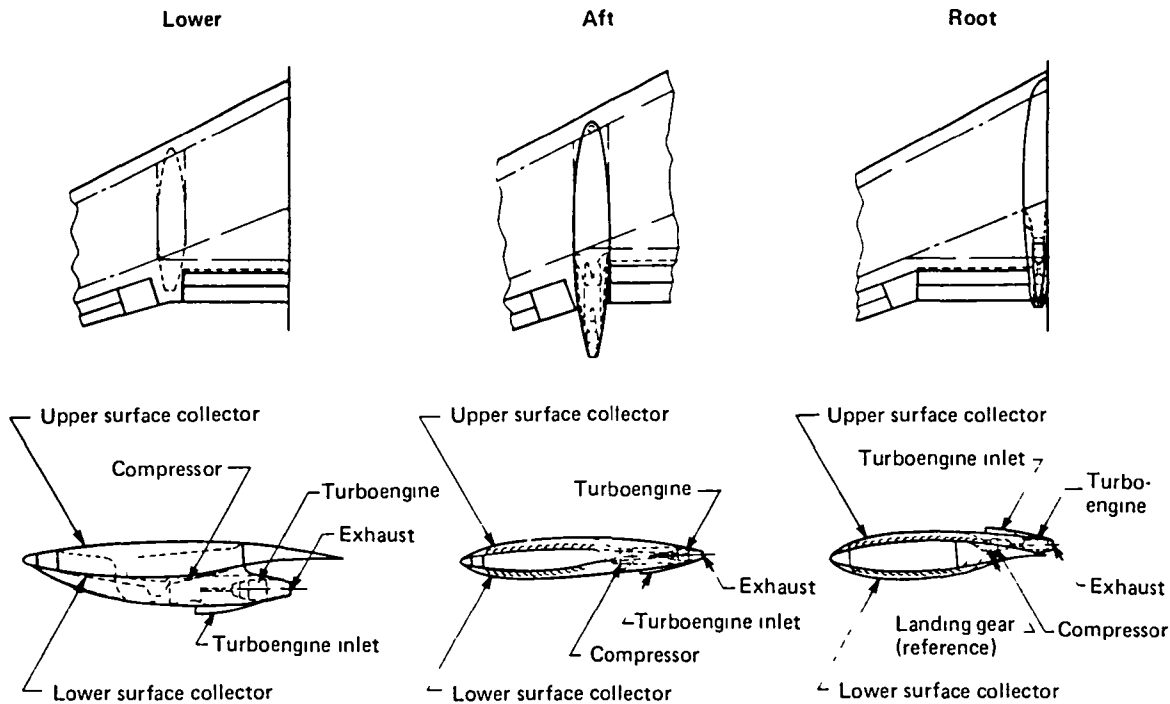


Figure 5-3-4. Options for Suction Unit Location on Wing

5.4 LEADING EDGE REGION CLEANING

Contamination of the wing leading edge by foreign particles such as insects or ice has been identified as a serious concern in all previous laminar flow studies and experiments where operational factors were considered. Of the two contamination problems, insect contamination (Ref. 20) has always been the most formidable. Elimination of ice can be handled in a straightforward manner and will be mentioned only briefly in this section of the report. Elimination of insects is an entirely different matter. Many solutions have been proposed in the past which were either impractical or posed serious operational problems. Several possible solutions, included in this section of the report, are recommended for further study.

5.4.1 DESIGN REQUIREMENTS AND OBJECTIVES

The primary design requirement for any leading edge cleaning or protection device is that it not cause premature transition of the laminar boundary layer. This requirement essentially eliminates any known type of mechanical device such as a scraper or deflector.

The design objective of a leading edge device to either clean or protect the leading edge is that it perform during both takeoff and landing approach and while operating within the insect layer, up to approximately 3,000 ft above the terrain. It is also an objective that such a device or system not require significant expenditure of ground maintenance personnel time for servicing between flights. It should be essentially self-contained and activated as necessary by the flight crew.

5.4.2 RECOMMENDED SYSTEMS

Leading edge cleaning or protection systems identified in this study were based on previous work in this field and contract efforts at design innovation. These systems are depicted in Figure 5.4-1 and are identified as the Liquid Film system, Cryogenic Frost system, and High-Pressure Air Shield system. These three approaches have the highest potential for success of any yet identified.

A liquid film system has been demonstrated in flight as an effective means of protecting the leading edge from insect contamination as discussed in Reference 21. It would operate by releasing water through the leading edge to wet the exterior surface during periods of expected insect encounter. The success of such a system would depend on the ability to design and maintain flush or hidden nozzles that would not trip the laminar boundary layer during cruise flight.

The high-pressure air shield has had no flight or wind tunnel test evaluation and whether or not such a system will actually work is not known. Also, the success of such a system is dependent on the ability to design flush or hidden nozzles that would not trip the laminar boundary layer during cruise. However, since air is used, no payload penalty would result due to carrying the protection medium

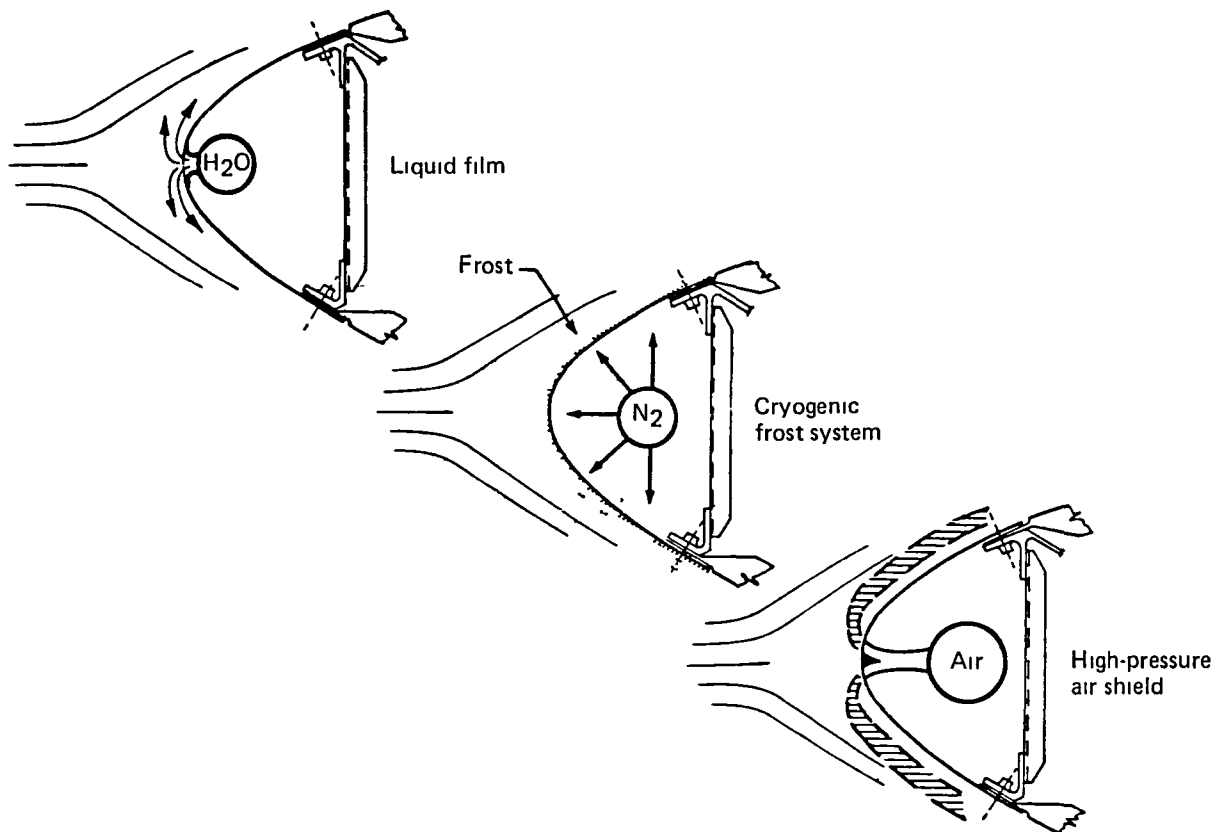


Figure 5.4-1. Leading-Edge Region Cleaning Concepts

onboard. And, like the liquid film system, this approach would work on landing approach as well as takeoff which would essentially eliminate ground cleaning between flights.

The Cryogenic Frost system is an innovation. The system is presented in schematic form in Figure 5.4-2. As shown it is combined with the hot air anti-icing system which is a very advantageous combination. The frost system operates on the principle of expanding liquid nitrogen into a mixing chamber to provide very cold air for distribution along the leading edge. The formation of frost on the leading edge prior to takeoff would occur through the natural moisture in the air condensing on the cold leading edge. During takeoff and climb, adherence of impinging insects would be inhibited by the frost. With shutdown of the system, the airstream would quickly melt the frost leaving a clean surface. The disadvantages of such a system are a lack of actual test experience and the fact that such a system would not work on landing approach. This would require cleaning the leading edge between flights. However, no penetration of the leading edge surface is necessary and only a small quantity of liquid nitrogen is required.

At this time no clear choice of leading edge protection system is apparent so further innovative design effort is highly desirable. As can be concluded from the above discussion, considerable additional development and testing effort is also needed before a satisfactory leading edge cleaning or protection system can be chosen.

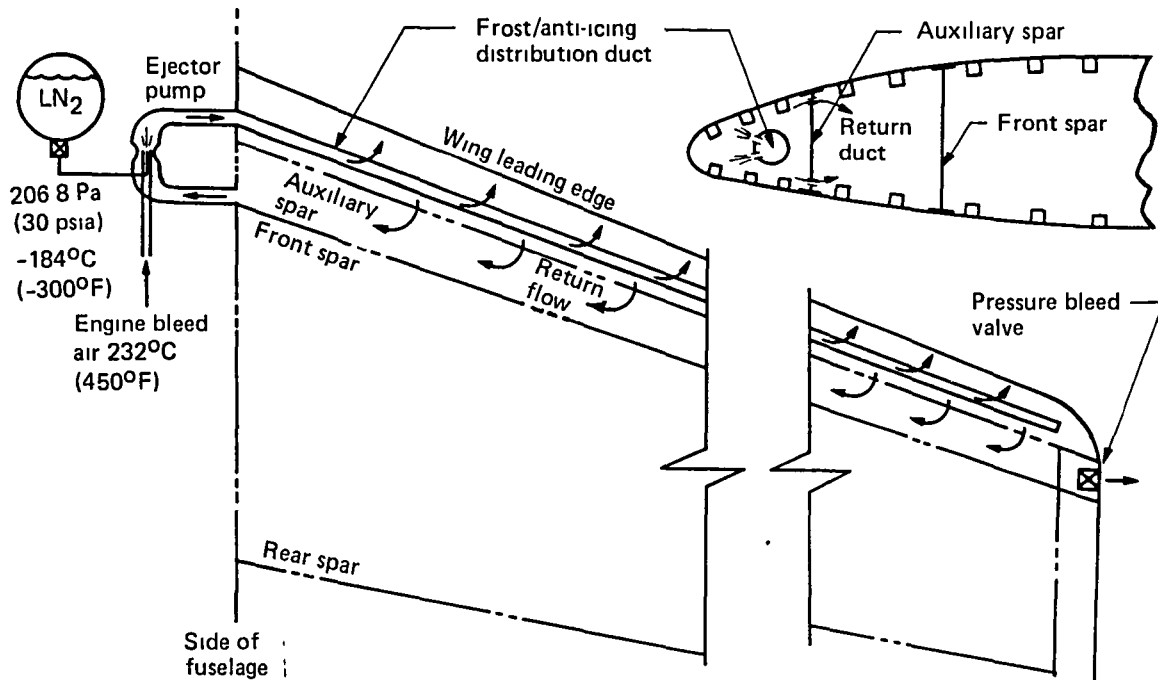


Figure 5.4-2. Wing Leading Edge Frost/Anti-Icing System Schematic

5.5 AUXILIARY SYSTEMS

Airplane auxiliary systems provide the functions other than propulsive thrust necessary to meet airplane operational requirements. Included are the hydraulic, pneumatic, electrical, electronic, environmental control, and high-lift systems. The objective of this task was to investigate the possible technical and economic benefits of integrating the LFC system with one or more of the auxiliary systems. Rationale for evaluation included improvement of performance and reliability, reduced maintenance, reduced cost, reduced weight and compatibility of installation space requirements.

Auxiliary systems and LFC systems integration studies are configuration dependent and must be conducted subsequent to final airplane configuration definition. However, preliminary airplane configuration studies have identified two areas where significant gain can be realized through combining auxiliary systems functions. In the leading edges, ducting systems and installation space are required for both hot air anti-icing and leading edge protection systems. Operation and control of both systems appears to present no incompatibilities since, for example, leading edge protection against insects would not be required during anti-icing operation.

Also, preliminary estimates indicate that the horizontal stabilizer suction unit power requirement would result in a power unit with sufficient capacity to meet the airplane ground APU requirement. However, provisions would be needed in the power unit design to match the compressor pressure ratio and airflow capabilities to meet both the LFC and ground APU requirements.

6.0 CONFIGURATION SELECTION AND DESIGN

The study activity under the subject task culminated in the definition of LFC systems to be incorporated in an integrated transport design which would be technically feasible and economically attractive for introduction to service in the early 1990's. The rationale for selection was based on (1) technical feasibility, (2) performance and benefits affecting economics versus cost, and (3) operational suitability. The results of the extensive concept evaluation studies previously discussed were used as a basis for systems selection and evaluation of the final configuration design. The performance of the selected airplane design is presented in Section 6.6 to provide a basis for eventual economic assessment of the airplane in airline service.

6.1 FINAL DESIGN REQUIREMENTS

Design requirements for the final LFC airplane fall into several categories. Since the airplane is a conventional layout and similar in many respects to a turbulent airplane design, the normal Federal Aviation Regulations (FAR) requirements are considered to be applicable unless otherwise stated. The airplane features associated with laminar flow and the corresponding systems can be expected to introduce some airplane characteristics which may require modification or extension of the FAR. At this stage of development, however, the potential impact of LFC on the FAR or certification has not been studied.

Prior to the definition of final design requirements, studies were undertaken to resolve such items as cruise altitude, climb requirements and fuel reserves to provide a rationale for defining such items.

The data in Table 6.0-1 give the final design requirements and show that the performance and mission-related values are unchanged from those used originally. However, on the basis of the studies referred to above, the cruise altitude has been reduced to 12 190m (40 000 ft) partly in recognition of the substantial economic penalty associated with higher than optimum cruise altitude.

The fuel reserve requirement has been extended to include a provision that, with LFC failure at the halfway point in the mission, the reserves be sufficient to reach the destination plus fuel for 15 minutes operation thereafter. The above reserve requirements are also compatible with normal airline and FAR requirements for engine failure en route.

6.2 AIRLINE CONCERNS AND RECOMMENDATIONS

Initially it was recognized that airline participation in the development of LFC design concepts could contribute substantially to the success of this effort. Thus the services of United Airlines (UAL) were secured for consultation to provide inputs, particularly on matters related to airline operations and economics. This participation has taken the form of periodic design reviews by responsible UAL personnel which have been reported during the course of the contract work. These reports have been furnished to NASA as received. Therefore, only the major

Table 6.0-1 Airplane Design Requirements

Item	Requirement
Design range	10 190 km (5500 nmi)
Payload	201 passengers
Cruise Mach number	0.8
Cruise altitude	12 190m (40 000 ft)(initial)
Turbulent climb capability	91.4 m/min (300 ft/min) at 10 670m (35 000 ft)
Takeoff field length	3566m (11 700 ft) (or less)
Approach speed	250 km/h (135 kn) (or less)
Fuel reserves	1967 ATA international rules (turbulent flow) or fuel to reach destination with LFC failure at halfway point

concerns and observations, taken directly from these reports, were presented (mostly verbatim) in the full contractor's report. These detailed discussions are not presented here, but it is emphasized that every effort has been made to configure the final LFC airplane to conform to airline recommendations.

6.3 PARAMETRIC STUDIES

During the course of configuration development and optimization, studies were conducted to determine the relative importance of various configuration characteristics which impact the overall performance, fuel consumption, and economics of an LFC transport. The airplane design parameters selected for the studies included wing sweep, wing aspect ratio, and engine bypass ratio. Within each of the studies, wing loading, thrust-to-weight ratio, and initial cruise altitude were varied parametrically. Configuration evaluations were based on the mission and performance requirements and constraints specified in Table 6.0-1.

The studies which led to the selected configuration took place over the duration of the contract and are illustrated schematically in Figure 6.0-1. The Initial Baseline Airplane was configured with a 25 deg wing sweep to get the benefit of substantial sweepback (i.e., higher thickness and greater span for reasonable wing weights) without incurring the severe crossflow instability and leading edge contamination occurring at higher sweepback. In order to evaluate the effects of wing sweep, a study configuration with $\Lambda = 15$ deg was developed. Supporting studies had shown that this value was needed to avoid suction slots in the leading edge forward of $x/c = 7\%$.

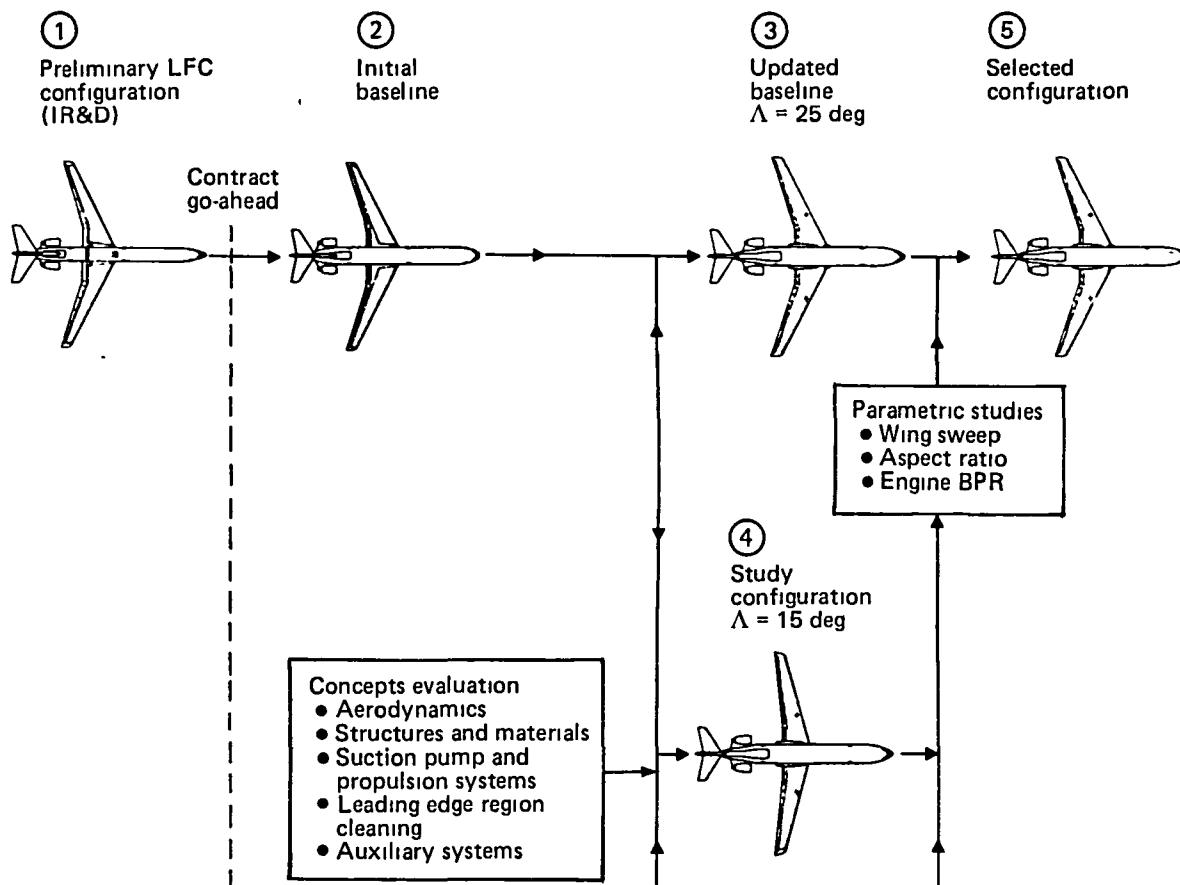


Figure 6.0-1. LFC Configuration Development

6.3.1 PARAMETRIC STUDIES RESULTS

The results of the individual parametric studies listed in Figure 6.0-1 are summarized as follows:

Wing Sweep

- Reduced sweep significantly increases gross weight and fuel burned.
- Sweep has no significant impact on wing loading or high-altitude cruise trends.
- Low sweep angle requires a thinner wing, which reduces structural efficiency and accessibility.

Aspect Ratio

- a. The choice of initial cruise altitude controls the economics, and increased aspect ratio slightly degrades direct operating cost (DOC).
- b. Increased aspect ratio has a large favorable effect on fuel efficiency; the choice of initial cruise altitude has a minor effect.

Engine Bypass Ratio

- a. Bypass ratio has little influence on fuel efficiency or economics.
- b. Aerodynamic integration and maintenance costs tend to favor low bypass ratio while fuel usage favors high bypass ratio.
- c. A two-stage fan may show improved fuel efficiency over a single-stage fan.

6.3.2 AIRPLANE GEOMETRY SELECTION

The overall results of the parametric studies indicate that the baseline wing geometry and engine bypass ratio should be retained for the final configuration. Therefore the parametric study design selections are:

Wing aspect ratio 10.0

Wing sweep 25.0 deg

Engine bypass ratio 7.3 (single-stage fan)

Relaxing the cruise altitude capability from the original objective of 12 800m (42 000 ft) to 12 190m (40 000 ft) at the design range-payload condition improves the airplane fuel efficiency and economics if the current objective for turbulent rate of climb can also be slightly relaxed. This appears a reasonable choice since most flights in actual service would be conducted at reduced gross weight conditions where cruise altitude capability would meet the original objective of 12 800m (42 000 ft).

6.4 TECHNOLOGY LEVEL AND IMPACT

Based on current technology programs and projections for development, the application of laminar flow control to a subsonic transport is a real possibility for the 1990 time period. Furthermore, advances in other technologies are also to be expected in this period based on existing programs in Government and industry. Thus a combination of compatible advances can logically be projected. The final LFC airplane configuration presented in this chapter is therefore conceived for introduction into service in the early 1990's. It incorporates the currently projected technology advances appropriate to this time period.

The listing given in Table 6.0-2 defines the advanced technology elements incorporated in the final airplane configuration and provides an assessment of the

Table 6.0-2. Advanced Technology Impact

	Δ Component weight	Δ (L/D)	Δ SFC
Aerodynamics Laminar flow control Advanced airfoil section Reduced roughness	To be determined -14% wing box -8% empennage	26% (33%)* 2% (3.5%)*	2.3% (2.7%)*
Active controls Reduced longitudinal stability Load alleviation	-20% horizontal tail -6% wing box	3%	
Propulsion Advanced turbofan (BPR = 7.3)	-13% engine		-14%
Advanced structures and materials Improved aluminum alloys Improved titanium alloys Bonded construction Graphite/epoxy composites Carbon brakes	-7% wing box -4% fuselage -4% empennage -20% heavy fittings -5% fuselage -25% trailing edge surfaces -27% wing box** -15% fuselage** -15% empennage** -10% landing gear		
Reference Existing levels			

*Applicable for laminarized wing and empennage

**Applicable if composites used in place of improved alloys and bonded construction

gains to be expected for each element based on application to the baseline airplane without recycling the design.

The weight penalties associated with LFC are substantial because of the basic need to provide viable suction surfaces in the laminarized areas and to include provisions for internal flow passages and distribution ducting to handle the suction air. The values shown in the table of Figure 5.2-4 correspond to unit weight penalties of slightly less than 4.79 Pa (1 lb/ft²) for the wing. An additional increment of 2.15 Pa (.45 lb/ft²) accounts for the weight of wing suction units and distribution ducting. A value of 4.06 Pa (.85 lb/ft²) was used for the horizontal tail LFC structure penalty in the laminarization studies for the empennage. Since the horizontal tail suction is provided by a unit which also serves as an APU (only slightly oversized for suction), the added unit weight penalty for the tail suction system is only 0.72 Pa (0.15 lb/ft²). The area base in all cases is the actual laminarized area.

6.5 FINAL CONFIGURATION DEFINITION

The final LFC airplane configuration incorporates the results of the entire series of tasks involved in the contract study. Of primary importance are those involving the alternative systems evaluations and selection, and the parametric trade studies used to determine the airplane arrangement and component sizing. The final combination consisted of those elements which best suit the airplane to economically perform the design mission and meet operational requirements representative of the airline operating environment.

6.5.1 GENERAL CHARACTERISTICS

Figure 6.0-2 shows the concept finally selected, namely, a long-range trijet of conventional layout incorporating laminar flow control on both wing and horizontal tail surfaces and the various advanced technology elements defined in the previous section. It is designed to meet the airline general operating requirements and the applicable FAR insofar as possible at this time. As previously stated, the mission requirements remain as originally defined for the baseline airplane and the final set

Range	10190 km (5500 nmi)
Payload	201 passengers (15/85 mix)
Gross weight	152 100 kg (335 000 lb)
Empty weight	84 970 kg (187 360 lb)
Wing	$S = 310 \text{ m}^2$ (3350 ft^2) ($\Lambda = 25 \text{ deg}$, $AR = 10$)
Engines	(3) 124.6 kN (28 000 lb) SLST (BPR = 7.3)
Mach number	0.80
Cruise altitude	12 190m (40 000 ft)

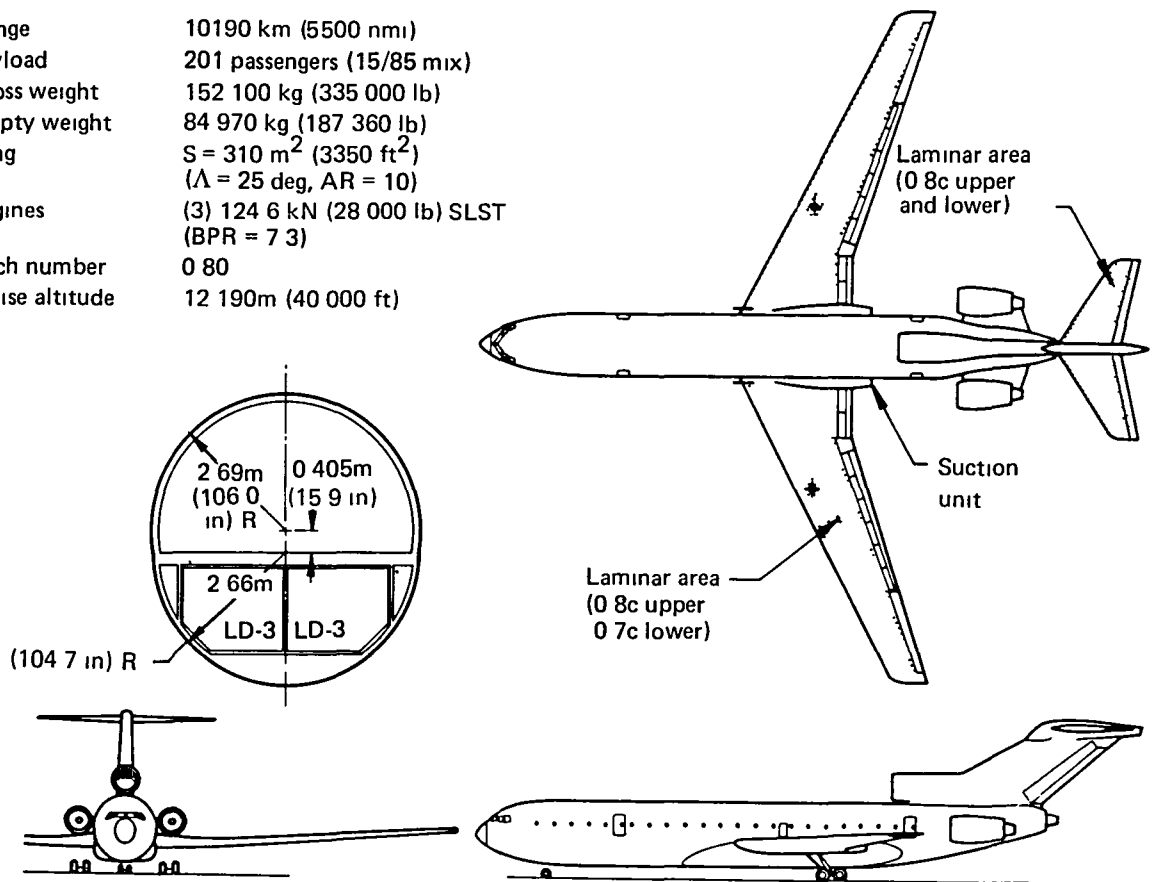


Figure 6.0-2. Final LFC Configuration—Model 767-811

of design requirements are as defined in Section 6.1. The passenger accommodations provide 7-abreast seating with two aisles and allow the use of 8-abreast for full economy configurations. Cargo is accommodated in two sections. The forward compartment is sized for 20 LD-3 containers; the aft compartment is available for bulk cargo.

The listing in Table 6.0-3 allows comparison between the final configuration (Model 767-811) and the baseline configuration (Model 767-807). While the overall arrangement is relatively unchanged, significant differences do exist which greatly improve the performance of the airplane. These differences are highlighted in the previous table. The rationale for selection of the various airplane features and their impact on performance are discussed in appropriate sections of this report.

6.5.2 SYSTEMS DEFINITION

The following paragraphs provide a general definition of the systems in the airplane which are either specifically related or unique to an LFC transport. Unless otherwise noted, the remaining systems would be designed to provide the essential services and meet the general design and regulatory requirements as normally required for turbulent transports.

Table 6.0-3. Configuration Characteristics Comparison

	Baseline configuration model 767-807	Final configuration concept
<u>Wing</u>		
Sweep/t/c	25 deg/0 11	25 deg/0 11
Aspect ratio	10	10
Wing loading	103	100
Flap-chord ratio	0 25	0 20
Laminarization	0 70c (upper and lower)	0 8c upper/0 7c lower
Structural concept	Laminated aluminum honeycomb (spanwise ducts)	Conventional structure/fiberglass cover (chordwise ducts/spanwise trunks)
<u>Empennage</u>	T-tail (turbulent flow)	T-tail (horizontal tail laminarized to 0 8 chord)
<u>Engines</u>	Aft body-mounted (BPR = 7 3)	Aft body-mounted (BPR = 7 3)
<u>Suction units</u>		
Wing { Compressor Drive Location	Two-pressure level Turboshaft Two, wing-mounted	Two-pressure level Turboshaft Two, side-of-body
Empennage	None	APU
<u>Leading edge</u>		
Insect removal	—	Choice open*
Anti-icing	Bleed air	Bleed air

*Systems need evaluation and validation

6.5.2.1 Airplane Systems General Considerations and Selection

Conventional environmental control, hydraulic, pneumatic, electric, and fuel systems are used. Modifications required to be compatible with the laminar flow control system are minimal and generally involve space routing provisions and flight control surface actuator locations. Airplane systems functions are integrated with LFC systems where performance requirements are similar.

6.5.2.2 LFC Systems

Section 5.3 describes the location and system trade studies that were accomplished to select the location and type of suction unit best suited to the LFC airplane. These studies led to selection of turbine engine-driven axial suction compressors located in the wing root. The design conditions for these baseline studies were 12 800m (42 000 ft) altitude, 0.8 Mach, standard day, and $C_L = 0.5$. Sizing of the units was initially based on providing suction for slots located from 0 to 70% chord on both upper and lower wing surfaces.

As airplane studies progressed, performance requirements for the suction system changed. The upper wing suction surface was increased to 0 to 80% chord, and design altitude and C_L were also increased. Since horizontal tail laminarization was incorporated in the final configuration and since power requirements were compatible with APU functions, the concept of a dual usage APU/suction unit was introduced. The APU configuration was therefore changed to permit its use for suction during flight. Provisions are included to allow the suction compressor to be unloaded and shaft power supplied to the airplane accessories for APU operation. Table 6.0-4 compares the baseline and final suction unit requirements and size and gives the design performance of the final system. Installation of the two wing units in the wing root and the horizontal stabilizer unit at the base of the fin above the center engine is illustrated in Figure 6.0-3.

Power for the wing and horizontal stabilizer leading edge protection systems (Section 5.4) will be provided by the airplane secondary power systems and will be determined by the protection system selected. A liquid film system will require electrical power for actuation control and fluid pumping. The high-pressure air shield will require a compressed air source (e.g., engine bleed) and electrical power for actuation and control. The cryogenic frost system will require electric power for actuation and control and a fluid circulating power source. Detailed trade studies are required to determine both power source selection and the degree of systems integration.

6.6 AIRPLANE PERFORMANCE CHARACTERISTICS

The final LFC configuration, Figure 6.0-2, is an aft-engine trijet with wing and horizontal tail laminarization.

The more important airplane size and performance characteristics are listed in Table 6.0-5. The engine size was determined by the initial cruise altitude requirement of 12 190m (40 000 ft). The wing loading was kept low to meet the approach speed objective and to keep the cruise C_L within acceptable limits without significant compromise in either DOC or fuel efficiency.

Table 6.0-4. Suction Unit Requirements, Size, and Performance

	Wing Units		Horizontal Stabilizer Unit
	Baseline*	Final	
Design conditions	h = 12 800m (42 000 ft) M = 0.8 C _L = 0.5 Standard day	h = 13 560m (44 500 ft) M = 0.8 C _L = 0.55 Standard day	h = 13 560m (44 500 ft) M = 0.8 C _L = 0.5 Standard day
Suction surface data Extent of laminarization, (x/c) _L			
Upper	0.70	0.80	0.80
Lower	0.70	0.70	0.80
Suction unit Corrected airflow, kg/s (lb/s)			
Upper	11.7 (25.7)	23.4 (51.6)	5.5 (12.13)
Lower	19.3 (42.54)	28.9 (63.74)	5.5 (12.13)
Suction engine shaft power, kW/unit (hp/unit)	246 (330)	383 (514)	112.9 (151.4)
Sea level equivalent power	1029 (1380)	1603 (2150)	546 (732)
Unit size (Dia.)			
Low pressure compressor	baseline	1.41 x baseline	Single stage suction compressor
High pressure compressor	baseline	1.224 x baseline	0.686 x baseline (low-pressure compressor)
Drive engine	baseline	1.33 x baseline	0.60 x baseline
Performance data (one unit)	h = 12 190m (40 000 ft) M = 0.8 C _L = 0.5 Standard day		h = 12 190m (40 000 ft) M = 0.8 C _L = 0.5 Standard day
Shaft power per unit, kW (hp)	177.5 (238)		117.4 (157.4)
Shaft power—total airplane, kW (hp)	355 (476)		117.4 (157.4)
Specific fuel consumption, kg/h/kW (lb/h/hp)	0.608 (0.5)		0.487 (0.4)
Fuel consumption, kg/h (lb/h)	108 (238)		47 (53)
Total fuel consumption (including 20% allowance), kg/h (lb/h)	315.5 (423) (all units)		

*Units sized for model 767-803

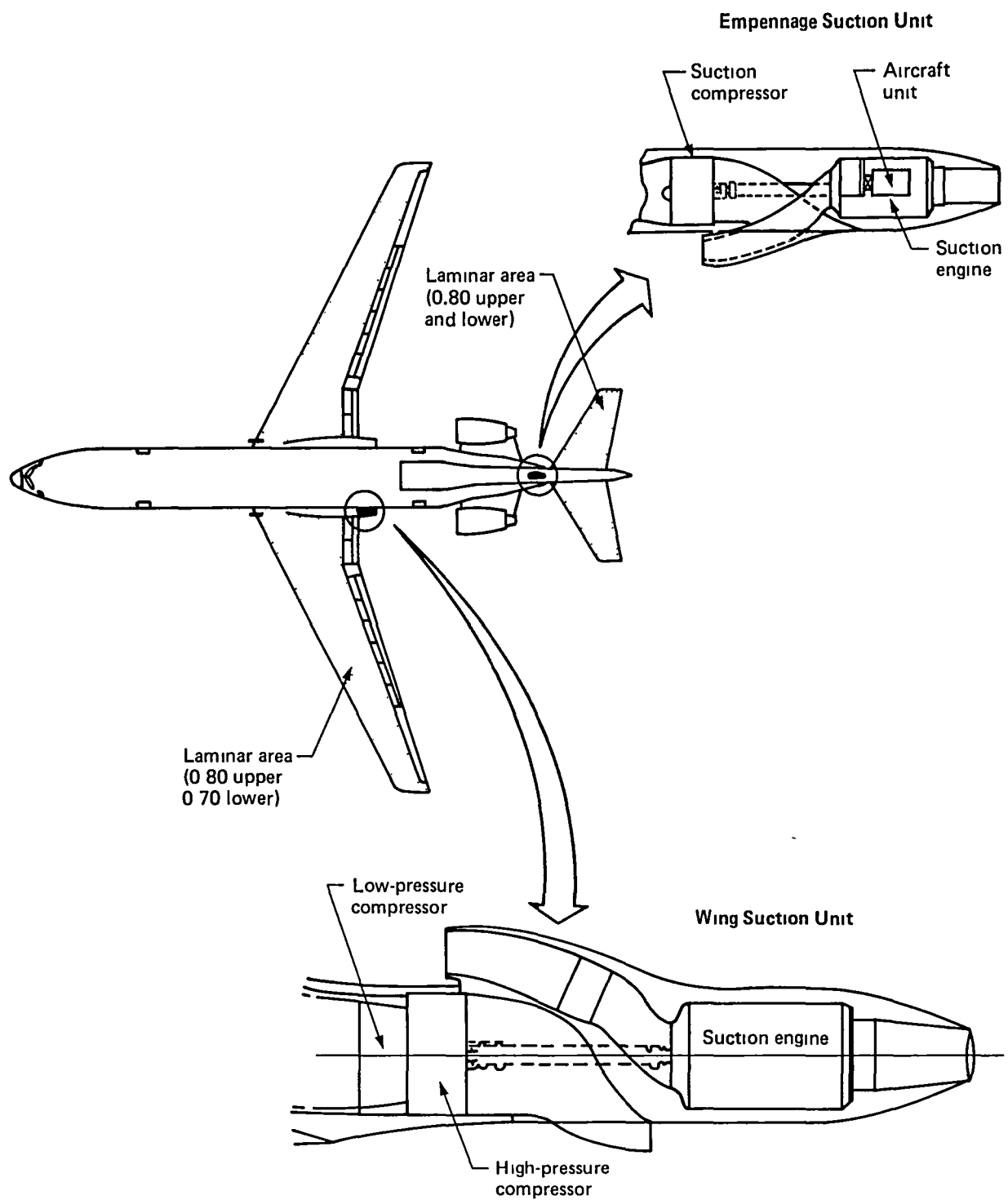


Figure 6.0-3. LFC Suction Unit Locations

Table 6.0-5. Airplane Performance and Characteristics—Model 767-811

- Cruise Mach No 0.80
- Payload 201 passengers
- Still air range 10 190 km (5500 nmi)
- Reserves 1967 ATA International
- Altitude, ICAC 12 190m (40 000 ft)
- Wing loading 490 kg/m² (100 lb/ft²)

Item	Value	
TOGW	152 100 kg	(335 030 lb)
OEW	84 970 kg	(187 320 lb)
Block fuel	41 890 kg	(92 260 lb)
Block time	12.36 hr	
Reserves	6 030 kg	(13 290 lb)
Mission landing weight	110 440 kg	(243 260 lb)
Wing area	310 m ²	(3350 ft ²)
Wing aspect ratio	10	
Wing sweep	25 deg	
Horizontal tail area	58.5 m ²	(629 ft ²)
Vertical tail area	48.5 m ²	(521 ft ²)
Body length	50.3m	(165 ft)
Body diameter	5.39m	(212 in)
Engine BPR	7.3	
SLST _{UNINST}	124.6 kN	(28 000 lb)
Range factor	34 300 km	(18 520 nmi)
(L/D) _{max}	25.5	
SFC	0.0635* kg/h/N	(0.6221* lb/h/lb)
FAR TOFL, SL 29°C (84°F)	2 440m	(8000 ft)
FAR landing field length (mission weight)	1 430m	(4700 ft)
Approach speed	246 km/h	(133.3 kn)

*Includes a 2.7% fuel flow for suction engines

6.6.1 BASIC PERFORMANCE

Figure 6.0-4 illustrates the payload-range performance of the final configuration. In the event of LFC failure at mid cruise weight, the design mission can be completed. Total fuel volume including center section tank is approximately 73 050 kg (160 900 lb), which is sufficient volume to offload the entire payload.

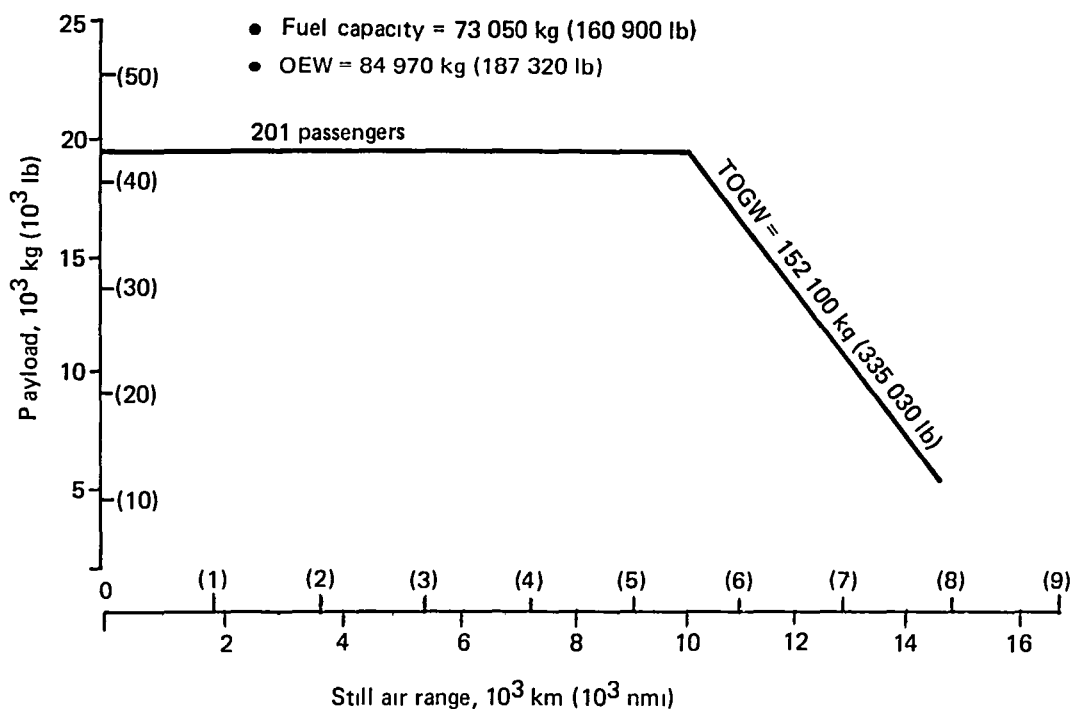


Figure 6.0-4. Payload-Range—Model 767-811

Figure 6.0-5 shows the fuel efficiency as a function of range. A comparison with the 747 airplane indicates a 70% improvement in fuel efficiency due to LFC and the other technology advances incorporated in the Model 767-811. The effect of LFC alone for a cycled design of this type is estimated to approach a 45% increase in fuel efficiency.

Takeoff and landing performance for the Model 767-811 is well within the original requirements set for the LFC airplane development. The FAR takeoff field length at sea level, 84°F, is only 2470m (8000 ft) and well below the objective of 11 700 ft. The FAR landing field length is 1570m (5150 ft) at maximum landing weight. The mission approach speed of 246 km/hr (133.3 kn) is slightly better than the original objective of 250 km/hr (135 kn) or less.

6.6.2 COMMUNITY NOISE

The noise characteristics of the final LFC study aircraft Model 767-811 have been estimated for an entry into service date in the 1990 time frame. Engine noise and nacelle acoustical treatment were estimated assuming technology levels forecast for conventional commercial jet transports in service in the same period. Three STF-482 (7.3 BPR) engines were assumed with maximum takeoff thrust of 124 684N (28 030 lb) SLST each and 270 km/hr (146 kn) takeoff speed, and an approach thrust of 27 041N (6160 lb) SLST at an approach speed of 250 km/hr (135 kn). The maximum takeoff gross weight was 152 400 kg (335 000 lb).

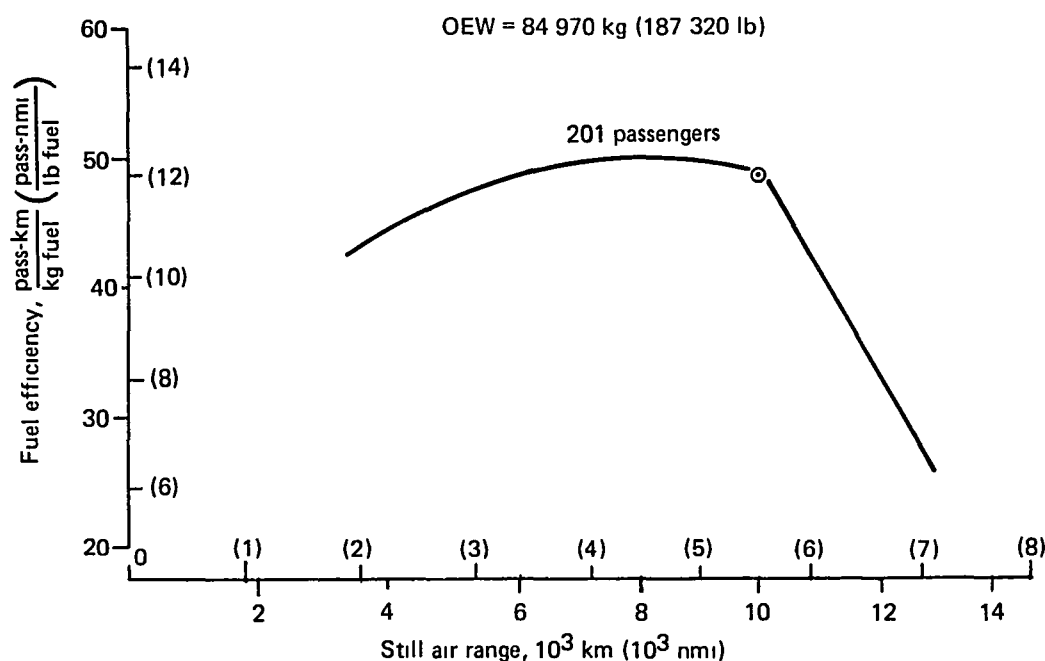


Figure 6.0-5. Fuel Efficiency—Model 767-811

The estimated noise levels at the three FAR 36-9 certification points are shown in Table 6.0-6 together with the latest (1978) FAR 36-8 noise rule levels for new aircraft with three engines and 152 100 kg (335 000 lb) maximum gross weight. Although noise level trades are allowed between the certification points (FAR 36-9) if required in order to meet the rule, these have not been used for the estimates. It will be seen that the estimated levels are below the required noise levels by 2 to 5 EPNdB, depending upon the certification point. However, the estimates shown are nominal values, and appropriate design or demonstration tolerances are required for certification or guarantee levels.

6.6.3 WEIGHT AND BALANCE

The mission sized LFC airplane, Model 767-811, has an operating empty weight (OEW) of 84 970 kg (187 320 lb). This is shown in Table 6.0-7 which also provides a weight breakdown for the principal components and systems of the airplane. A preliminary balance evaluation of this configuration shows an acceptable loadability between the center of gravity limits of 5% to 39% MAC. A maximum of 12 LD-3 containers in the forward lower level cargo hold may be used with a full passenger load. Cargo density of 160 kg/m^3 (10 lb/ft^3) is assumed. Full forward lower level cargo loading may be used if aft bulk cargo provisions are incorporated in the airplane design.

Table 6.0-6. Community Noise for Model 767-811

	Takeoff ¹ EPNdB	Sideline ² EPNdB	Approach ³ EPNdB
Model 767-811*	94 0	94 5	101 0
FAR 36-8 rule [†] for new aircraft	98 7	99 4	102 9

¹6500m (3 5 nmi) from brake release

²450m (0 25 nmi) to sideline

³2000m (1 08 nmi) from approach

*Nominal estimates shown, appropriate design/demonstration tolerances required for certifiable/guarantee levels

[†]No trades used

Table 6.0-7. Weight Statement for Model 767-811

Item	Weight, kg (lb)	
Total structure	49 850	(109 900)
Wing	17 700	(39 010)
Empennage	3 990	(8 800)
Body	17 130	(37 770)
Nacelle	4 040	(8 910)
Gear	6 990	(15 410)
Propulsion system	7 510	(16 550)
Fixed equipment and options*	20 570	(45 350)
Standard and operating items	7 040	(15 520)
Operating empty weight (OEW)	84 970	(187 320)

* Includes suction unit weights for wing and empennage laminarization

7.0 CONCLUSIONS AND RECOMMENDATIONS

Results of the NASA-sponsored LFC technology development effort in Phase I have shown significant progress and indicated the potential for airplane operating cost reductions and substantial fuel savings. Airplane design work conducted during the contract and augmented by Boeing-sponsored independent research and development has actively supported this development by closely following or anticipating technology advances and solutions to critical problems (Ref. 22).

Aerodynamic Design

The aerodynamic design of an LFC wing has been developed to the point where it could serve as a basis for further refinement in the wind tunnel. Advanced high-speed airfoils have been shown to be compatible with LFC requirements and to provide a reasonable envelope to incorporate LFC systems and ducting. Nevertheless, continuing development of advanced high-speed airfoils for modern wing design is important to provide increased wing thickness and reduced weight with no reduction in speed. The impact of such development is even more favorable for LFC airplanes since their requirements for wing volume and controlled pressure distributions are more demanding than for turbulent airplanes. While the current aerodynamic design appears viable, further optimization is necessary to minimize drag and reduce internal flow losses. Further objectives should include reducing sensitivity to off-design operation and various disturbances, minimizing the number of slots and reducing the criticality of the leading edge. Ultimately, validation of the aerodynamic design is required throughout the operating envelope.

Recent advances in laminar boundary layer development and stability theory provide important new aids for the aerodynamic design of LFC wings. There is, however, a need for further validation and automation of methods to facilitate design decisions. New methods are needed to analyze the local effects of flow through suction surfaces including disturbances generated in this process. Ultimately, a complete three-dimensional analysis involving all possible modes including sound, may be necessary to provide a valid theoretical basis for predicting suction requirements in the presence of disturbances associated with the flight environment.

Wind Tunnel Testing

Wind tunnel testing is an essential supporting activity to provide basic data for design decisions which result in airplane performance improvements. The implementation of a wind tunnel test program by Boeing and the achievement of all major test objectives represents a first step toward filling these needs which should contribute to the advancement of LFC technology. Particularly significant results achieved during these tests include:

- a. Validation of the Boeing Research Wind Tunnel and the current test arrangement as a suitable facility for conducting laminar flow research on swept wings.
- b. Successful evaluation of a leading edge design for LFC on a swept wing at near-full-scale Reynolds numbers and accumulation of valuable experience in

coping with the realities of achieving laminar flow in a less than ideal operating environment.

- c. Determination of the sensitivity of LFC to suction inflow distribution and to off-design operation.
- d. Extension of transition criteria for both two-dimensional and three-dimensional surface protuberances to include the effects of crossflow and suction quantity.
- e. Achievement of a better understanding of interactions between sound fields and the controlled laminar boundary layer, and development of preliminary criteria for tolerable sound levels on a swept wing.

Wind tunnel testing should be continued in fundamental areas and extended to support design development and evaluation prior to committing to major flight programs.

Structural Approaches

The search for satisfactory solutions to the structural and systems problems imposed by the requirements for maintaining laminar flow has involved the consideration of a large number of alternative concepts and arrangements. This has resulted in the development of at least twelve different structural approaches involving the use of advanced structural arrangements and materials. These have been subjected to critical evaluation and review resulting in the selection of the conventional structure with fiberglass cover arrangement, which is well-suited to application in the near term. It can also be readily applied to almost any structural arrangement, including those using graphite/epoxy composites. The use of such composites in wing structure has been shown to be compatible with LFC requirements and to provide outstanding weight reduction potential. However, on the basis of current and foreseeable development activity, it is considered to be applicable only in the longer term. For the near term, a feasible structural concept has been defined which shows promise of providing a practical design that can be built and operated for reasonable cost. However, extensive design development is still required to reduce weight and cost and to resolve operational and manufacturing concerns. Validation of the concept by analysis and tests is an essential step in advancing the design to a state of readiness for production.

LFC Systems

The major additional systems requirements due to LFC are associated with the wing suction distribution and ducting systems and the suction compressor and drive. The important options for the elements of such systems, including their location on the airplane, have been evaluated and the overall arrangement selected. The wing suction units, each consisting of a two-pressure level compressor with turboshaft engine drive, are located at the trailing edge of each wing-body intersection. Suction for the horizontal tail is provided by an APU which retains its normal function for ground operation.

In the category of special systems, protection against the accumulation of insects at the wing leading edge is of critical importance. Several promising candidates

for such a system have been identified and assessed for technical feasibility. These involve the use of (1) a liquid film (water plus anti-freeze), (2) a cryogen (liquid nitrogen) expanded into the leading edge cavity to produce frost on the leading edge, and (3) an air shield using high-velocity jets. These must be subjected to further analysis and testing under simulated operational conditions and eventually integrated into a total leading edge design for evaluation in flight.

Operational Problems

Key operational problems have been identified and explored, the most important of which are: (1) wing leading edge damage, (2) insect contamination, (3) operational reliability, particularly in the presence of ice clouds and (4) a need for procedures and techniques that will provide low-cost maintenance and repair characteristics. Solutions to these problems must be developed and validated either in the laboratory or in flight before serious consideration of LFC application can be expected.

LFC Transport Design Trends

An LFC transport configuration has been developed incorporating the most promising structural arrangement and system concepts developed during this study. Combining other elements of advanced technology with LFC provides attractive fuel utilization benefits which will have a very favorable impact on airplane economics. Nevertheless, further trade studies are needed to define the combination of features that will lead to a design most competitive with a turbulent airplane. In particular, more work is necessary to establish better design criteria and operational requirements. In this connection, cruise altitude and turbulent climb capability have been shown to have a major influence on the geometric definition of the long-range LFC transport to provide near-optimum performance and economics. For example, configurations tend toward lower wing loadings and thrust loadings and somewhat higher aspect ratios than for turbulent aircraft. The wing sweep will tend toward a near-optimum value based on wing weight (25 deg sweep at $M = 0.8$). However, the final sweep selection should be based on the careful consideration of the sensitivity of laminar flow to sweep and leading edge design details. The compromise must be strongly biased by the need to maintain LFC with high reliability in the airline operational environment.

It is recognized that the work under existing Phase I contracts represents only a start toward full-scale system design and that further work is required in technology development and testing of advanced structural and systems concepts. The LFC program should continue to focus on hardware design and development leading to construction of a validator airplane. This is essential to provide the practical experience needed to determine the operational and economic feasibility of introducing LFC transport aircraft onto commercial airline routes in the foreseeable future.

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